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Problems in the Control of Anthracite Mine Fires: A Case Study of the Centralia Mine Fire (August 1980)

By Robert F. Chaiken, Robert J. Brennan, Bernice S. Heisey,
Ann G. Kim, Wilbert T. Malenka, and John T. Schimmel

UNITED STATES DEPARTMENT OF THE INTERIOR

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PREFACE

This Report of Investigations is based in part on a report of studies of the Centralia mine fire prepared under Interagency Agreement J5101026 (December 31, 1979) between the U.S. Department of the Interior Office of Surface Mining (OSM) and the Bureau of Mines. Numerous copies of the original Bureau report, "Problems in the Control of the Centralia Mine Fire" (dated August 15, 1980), have been distributed locally by OSM to the citizens of Centralia and other interested parties.

The Bureau of Mines, in developing the original report to OSM, undertook an examination of a large amount of data dealing with anthracite mine fires and their control, in general. From these studies and an evaluation of the available information on the Centralia mine fire, a number of specific control methods for Centralia were evaluated in detail, technically and economically. Because the Bureau believes that the methodologies developed in this work constitute an advancement in the state-of-the-art of mine fire evaluation, and can have general application to other abandoned coal mine fires, this report has been written to provide an archival record of the work.

It shall be noted that three years has passed since the original Bureau report to OSM, and the Centralia mine fire is likewise three years older. Hence the conclusions in this report as applied specifically to Centralia must be reexamined in light of more current information on the fire.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cu yd	cubic yard	μm	micrometer
gal/min	gallon per minute	pct	percent
HP	horsepower	ppm	part per million
m	meter	rpm	revolution per minute
M	thousand	sq mi	square mile
MM	million	vol pct	volume percent

PROBLEMS IN THE CONTROL OF ANTHRACITE MINE FIRES: A CASE STUDY OF THE CENTRALIA MINE FIRE (AUGUST 1980)

By Robert F. Chaiken,[1] Robert J. Brennan,[2] Bernice S. Heisey,[3] Ann G. Kim,[4]
Wilbert T. Malenka,[5] and John T. Schimmel[2]

ABSTRACT

The Bureau of Mines has conducted a study of mine fires in the Anthracite Region of Pennsylvania to determine the most effective approaches to fire control in this area. The problems involved in controlling an anthracite fire include the geological and mining conditions in this area, the propagation characteristics of anthracite, the fire control methods available, the hazards associated with these fires, and the marginal effectiveness of past fire control projects. From this general background, fire control options were discussed as they apply in 1980 to the Centralia mine fire. Probable effectiveness, feasibility, and costs were assessed. The options evaluated include four excavation plans, flooding, hydraulic flushing, water curtain isolation, mining to construct an underground barrier, burnout control, and relocation of the community. The most advantageous from a technical viewpoint is an excavation method combining complete excavation of the fire zone within the borough with trenching to confine the remaining fire. It appears that for many anthracite fires, as for the Centralia mine fire, there are no available control measures that have a moderate cost, are proven effective, and produce minimal disruption on the surface.

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INTRODUCTION

Past experience with anthracite mine fires in northeastern Pennsylvania has demonstrated that mine fires in this region are especially difficult and costly to control. In some cases, these fires have outlasted repeated control efforts for more than a decade or recurred after they were thought to be extinguished. As the area and intensity of a fire increase, so do the potential hazards to the environment, property, and in particular, to the health and safety of nearby inhabitants.

Fire control methods that have been applied successfully in bituminous coalfields are less effective in the Anthracite Region because of the steeply pitching, sharply folded, and broken nature of the coal-bearing strata and the extensive, abandoned mined-out areas underground. A 1977 Bureau study of 16 of the 26 coal-producing States records 12 current fires in abandoned mines and inactive coal deposits in the Anthracite Region (8).[6] Although this figure represents less than 5 pct of the total, it is a sizable number in an area containing just 484 sq mi of workable coal. Considering the population density of the area and the difficulty experienced in past fire control efforts, these fires are an especially serious concern.

In order to understand the specific problems involved in handling a mine fire in the Anthracite Region, it is useful to examine a specific case in some depth. In 1980 the Bureau conducted a detailed study of the Centralia mine fire for the Office of Surface Mining, as a basis for renewed fire control efforts. While mine fires often have individual characteristics, there are sufficient similarities between fires to make the Centralia mine fire a useful case study of the problems involved in controlling anthracite mine fires.

A fire in the Buck Mountain Coalbed near Centralia Borough, Columbia County, PA, was discovered in May 1962. After 21 years and the expenditure of more than $3 million, the fire in the abandoned underground workings is not yet under control. It currently affects a surface area of about 140 acres and is a hazard to nearly one-third of Centralia Borough and an immediate hazard to the nearby village of Byrnsville.

This report includes a discussion of the geology of the Anthracite Region, the factors affecting the propagation of anthracite mine fires, and the methods available for their control in general, and as they apply to the unsuccessful fire control efforts at Centralia. Information on past fires and the fire control methods employed are examined in an attempt to establish both hazard and effectiveness criteria that can be applied to anthracite mine fires in general as derived from a study of the mine fire problem at Centralia. While various options for controlling the fire are also discussed in terms of impact on the community, effectiveness, and costs, this report shows that for many anthracite fires, there are no currently available control measures that have a moderate cost, are proven effective , and produce minimal disruption to people and property.

ACKNOWLEDGMENTS

The compilation of this report was made possible by the combined efforts of a relatively large number of Bureau personnel at the Pittsburgh Research Center (Bruceton, Wilkes-Barre, and Schuylkill Haven facilities). Significant contributions to the work reported here were made by Robert Bentz, Arthur Damick, Jack Delaney, Earl Gradwell, Roland Harper, David Hyman, Dan Lewis, Arthur Miles, Dorothy Narcovich, John Stockalis, John Vasilauskas, and Ivor Williams.

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[6] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

GEOLOGY OF PENNSYLVANIA ANTHRACITE

Anthracite underlies about 484 sq mi of northeastern Pennsylvania in 10 counties: Carbon, Columbia, Dauphin, Lackawanna, Lebanon, Luzerne, Northumberland, Schuylkill, Susquehanna, and Wayne (7). The region is divided into four separate, but contiguous fields (the Northern, Eastern Middle, Western Middle, and Southern), which trend along the northeast-southwest alignment of the ridge and valley province of the Appalachians (fig. 1). Each field lies within one or more deep, steep-sided synclinal basins rimmed by ridges.

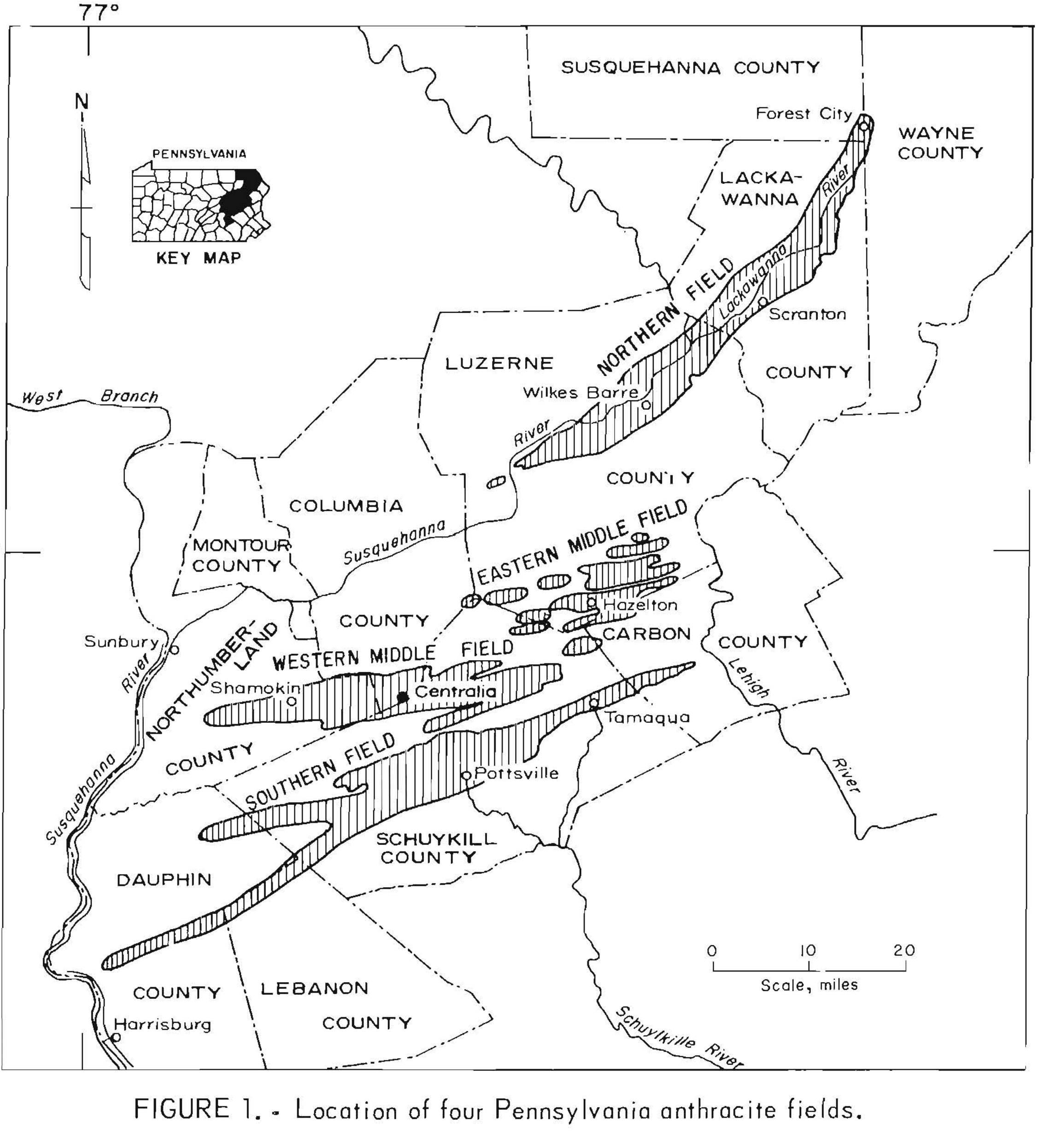
77°
41°
N
PENNSYLVANIA
KEY MAP
SUSQUEHANNA COUNTY
Forest City
WAYNE COUNTY
LACKAWANNA
Lackawanna River
NORTHERN FIELD
Scranton
LUZERNE COUNTY
Wilkes Barre
River
West Branch
COLUMBIA COUNTY
MONTOUR COUNTY
Susquehanna
EASTERN MIDDLE FIELD
Hazelton
CARBON COUNTY
Sunbury
River
NORTHUMBERLAND COUNTY
WESTERN MIDDLE FIELD
Shamokin
Centralia
Tamaqua
Lehigh River
SOUTHERN FIELD
Pottsville
Susquehanna
SCHUYLKILL COUNTY
DAUPHIN COUNTY
Harrisburg
LEBANON COUNTY
Schuylkille River
0
10
20
Scale, miles

FIGURE 1. - Location of four Pennsylvania anthracite fields.

Coal was deposited here in flat-lying beds during the Pennsylvanian period, contemporaneously with the bituminous coal of Appalachia. This eastern part of the Appalachian Basin later was folded during the mountain-building periods of the Permian age, resulting in the ridge and valley topography (5). Later periods of erosion destroyed all coal measures in eastern Pennsylvania except for those preserved within the deep synclinal folds; thus, the coalfields generally occur in the center of synclinoria or composite fold systems. As a general rule, the dips in the Northern Field are more gentle and uniform than those in the other fields, and moving southwest to the Western Middle Field and the Southern Field, the basins are deeper with steeply dipping sides (23). The coalbeds lie in synclinal troughs, which are relatively flat at the center and moderately to steeply pitching along the limbs. The dip of the beds ranges from 0° to 90°, and in some places the beds are inverted as a result of intense folding during the Appalachian orogeny. Further evidence of the pressure and heat of this tectonic activity is the conversion of the coal to the higher rank anthracite.

The anthracite-bearing rocks are of Pennsylvanian age and consist of conglomerate, sandstone, siltstone, claystone, shale, and coal. Strata are highly folded and faulted, and the anthracite occurs as discontinuous, multiple beds separated by varying thicknesses of rock strata (fig. 2). The depth of the lowest bed is 1,700 feet. The coal-bearing rocks are divided into the Pottsville and Llewellyn Formations (fig. 3). The Pottsville Formation, occurring between the Mauch Chunk and Llewellyn Formations, may contain as many as 11 coalbeds of variable thickness. The Llewellyn Formation, occurring between the Pottsville and the erosional surface, may contain eight persistent coalbeds.

The Centralia mine fire is located in the Western Middle Field, which covers 94 sq mi, in Northumberland, Columbia, and Schuylkill Counties. There are six major basins in the Western Middle Field: the Mahanoy, Shenandoah, Centralia, Shamokin, Coal Run, and Mount Carmel. The fire is located in the Centralia basin along the north and south limbs of the Locust Mountain anticline (fig. 4). Although the basins are separated by anticlines and faults, they are often interconnected by mine workings. In the Western Middle Field, the lowest coals are the five Lykens Valley Coalbeds of the Pottsville Formation; only one of these is persistent throughout the field. At the base of the Llewellyn Formation is the Buck Mountain Coalbed. It may be divided into two splits separated by as much as 80 feet of rock. In the Western Middle Field, the Buck Mountain averages 6-1/2 feet of coal. The Seven Foot Coalbed occurs 30 to 100 feet above the Buck Mountain. The Skidmore Coalbed is 4 to 6 feet thick and occurs 50 to 150 feet above the Seven Foot Coalbed. The Mammoth coal zone is 200 to 300 feet above

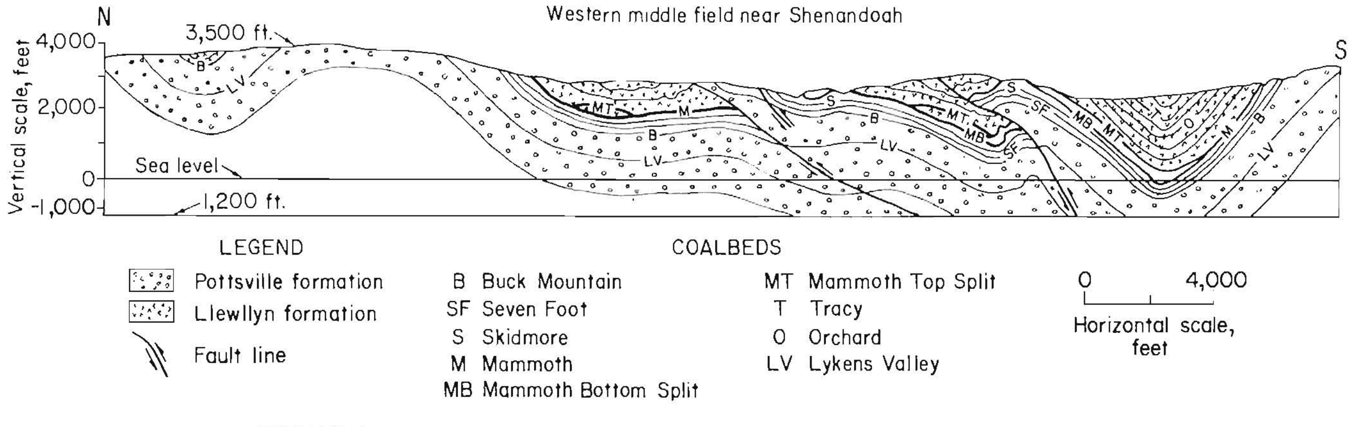
N
S
Western middle field near Shenandoah
Vertical scale, feet
4,000
2,000
0
-1,000
3,500 ft.
Sea level
1,200 ft.
B
LV
MT
M
S
SF
MB
O
LEGEND
Pottsville formation
Llewllyn formation
Fault line
COALBEDS
B Buck Mountain
SF Seven Foot
S Skidmore
M Mammoth
MB Mammoth Bottom Split
MT Mammoth Top Split
T Tracy
O Orchard
LV Lykens Valley
0
4,000
Horizontal scale, feet

FIGURE 2. - Generalized cross section of Western Middle Field.

the Buck Mountain. It generally consists of Bottom and Top Splits, although it may vary from a single thick coalbed to a 150-foot zone containing as many as four splits. The Holmes, Primrose, Orchard, Diamond, Tracy, Peach Mountain, and Tunnel Coalbeds occur in some areas of the Western Middle Field, but the strata containing these coals have been removed by erosion at the site of the Centralia fire.

OBSERVATIONS ON ANTHRACITE MINE FIRES AND THEIR CONTROL

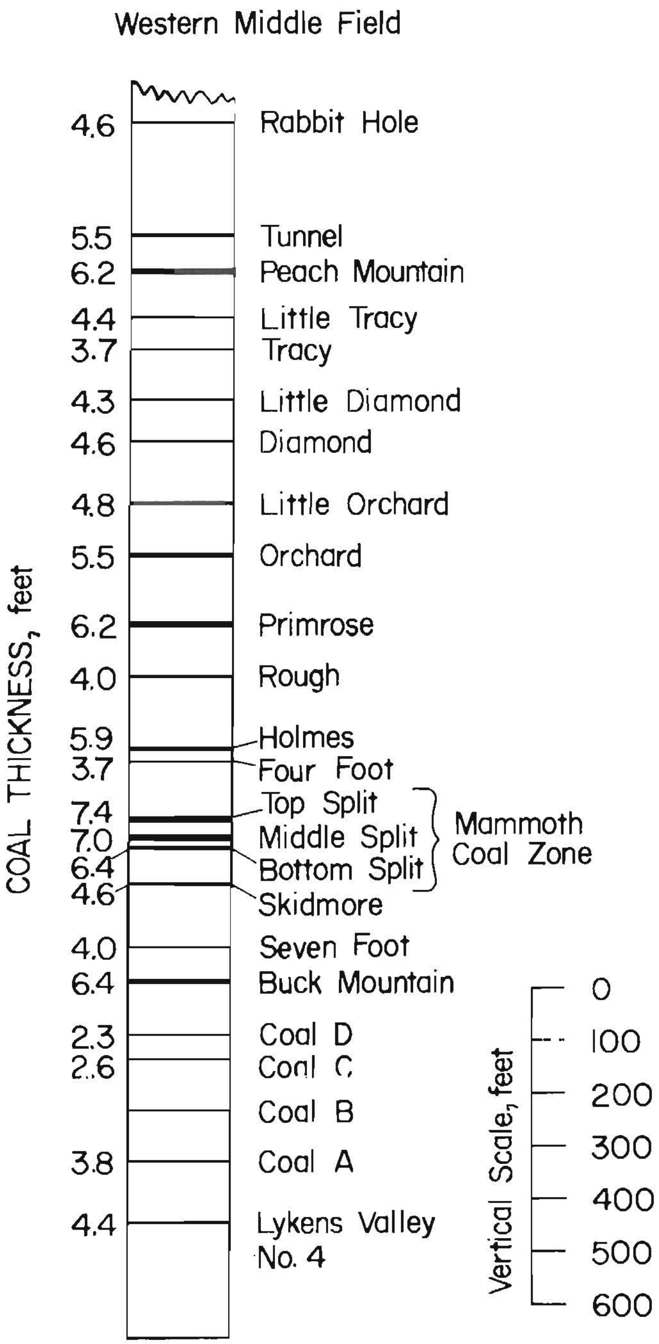
Western Middle Field
COAL THICKNESS, feet
4.6 Rabbit Hole
5.5 Tunnel
6.2 Peach Mountain
4.4 Little Tracy
3.7 Tracy
4.3 Little Diamond
4.6 Diamond
4.8 Little Orchard
5.5 Orchard
6.2 Primrose
4.0 Rough
5.9 Holmes
3.7 Four Foot
7.4 Top Split
7.0 Middle Split
6.4 Bottom Split
Mammoth Coal Zone
4.6 Skidmore
4.0 Seven Foot
6.4 Buck Mountain
2.3 Coal D
2.6 Coal C
Coal B
3.8 Coal A
4.4 Lykens Valley No. 4
Vertical Scale, feet
0
100
200
300
400
500
600

FIGURE 3. - Generalized stratigraphic section of the Western Middle Field. All coalbeds above the Mammoth have been eroded in the Centralia area.

During the course of the Bureau's assessment of the Centralia mine fire problem, the history of mine fires in the Anthracite Region and their control was reviewed in some detail. Although no two mine fires should be considered identical, some general observations can be made that are pertinent to the problems at Centralia. Mine fire behavior patterns were discussed in a 1938 publication by McElroy (13); although that study dealt with fires in active mines, many of the observations can also be applied to recent fire control projects in abandoned mines, including Centralia.

In addition to the comprehensive study by McElroy, which covered the years 1850 to 1936, recent fire control projects were reviewed as well as current assessments of borehole data on the Centralia fire, and field and laboratory data related to spontaneous combustion of coal.

In this section, fire control methods and the general behavior of major anthracite mine fires are reviewed and assessed in terms of the effectiveness of control techniques. From these observations, a picture of fire propagation is postulated that provides a logical basis for discussion of various fire control options, as developed for the Centralia fire.

BASIC METHODS TO CONTROL FIRES IN ABANDONED COAL MINES

There is no one method used to control or extinguish all underground mine fires. The characteristics of each fire determine which method or combination of methods has the greatest probability of success. The methods currently used to control or extinguish anthracite mine fires are essentially those described by McElroy (13) in 1938 and expanded upon by

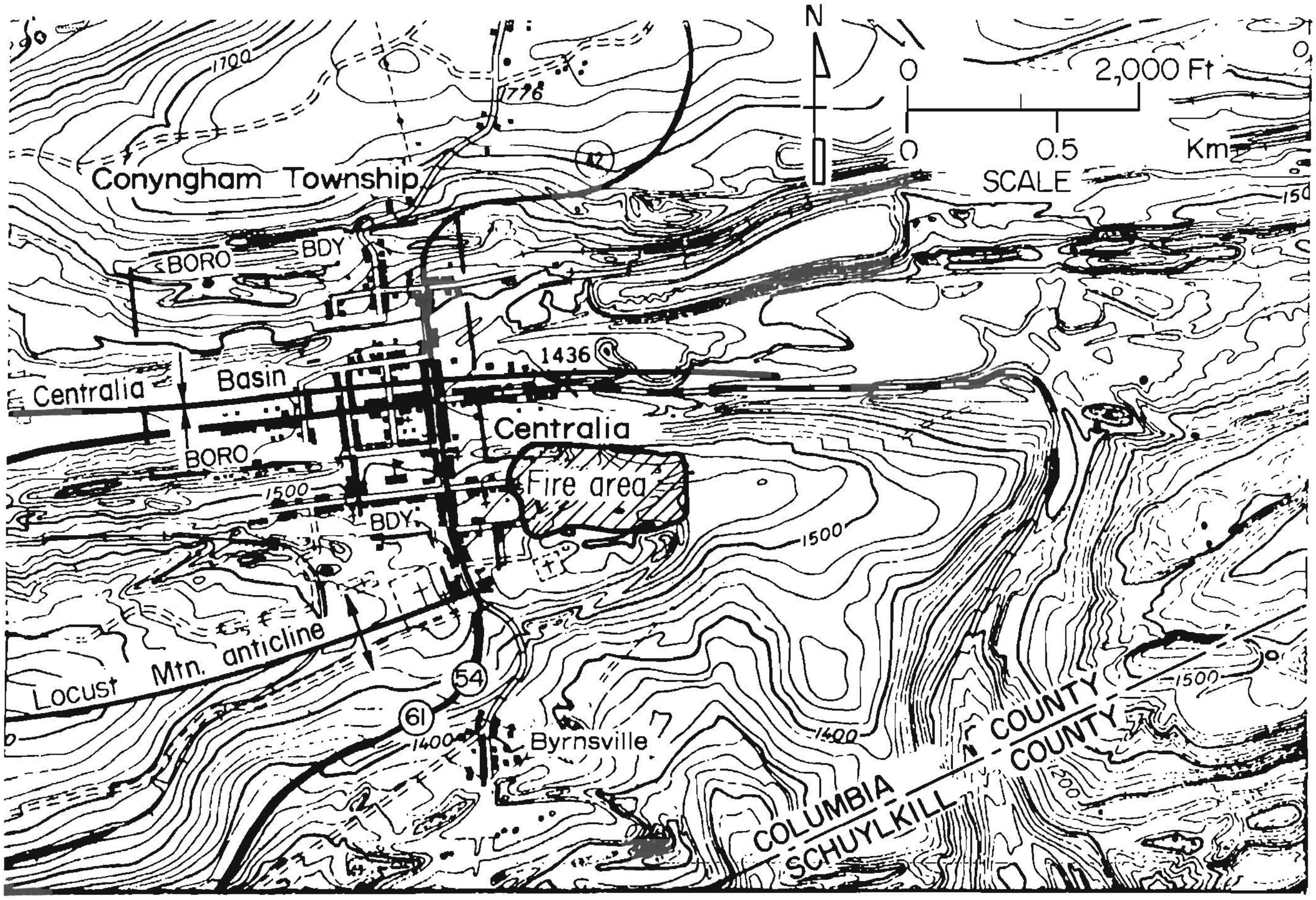
N
0
2,000 Ft
0
0.5
Km
SCALE
1700
776
42
Conyngham Township
BORO
BDY
1436
Centralia
Basin
Centralia
BORO
1500
BDY
Fire area
1500
Locust Mtn. anticline
54
61
1400
Byrnsville
1400
1500
COLUMBIA COUNTY
SCHUYLKILL COUNTY
1200

FIGURE 4. - Location of Centralia fire zone, Locust Mountain anticline and Centralia basin.

Griffith (6) in 1960 and Magnuson (12) in 1974. These include loading out (or excavation), inundation, installation of fire barriers, flushing, and surface sealing.

Other methods such as the use of inert gases, steam, and liquid chemicals have been proposed and/or attempted; however, these methods have not been given serious consideration because of costs and technical problems.

A fire requires fuel, oxygen, and heat. Removing fuel, eliminating oxygen, or cooling below the ignition temperature of the fuel will extinguish a fire. The extinguishment or control method used depends upon which has the greatest probability of success and on factors limiting its application. Each fire is unique, and circumstances that must be considered include the extent of fire either below the surface or along an outcrop, the threat to the environment, the proximity to built-up areas, the geological and topographical conditions (including the pitch, the number, and the thickness of coalbeds), the extent of mining, and the type of overburden. Other nontechnical factors, such as participation of local governments, the effect on the health and well-being of residents, and releases or condemnation proceedings to acquire properties, must also be considered in selecting the control method(s).

The following is a brief description of the basic methods that have been employed separately or in combination in mine fire extinguishment and/or control projects.

Excavation

The excavation (loading out, digging out, or stripping) method is a direct control effort that is generally feasible if it is started soon after a fire is discovered. Loading-out involves physically removing the burning material and quenching it to extinguish the fire. The location of the fire will generally determine if it is economically feasible, and the extent of the fire will determine if excavation will be able to safely stay ahead of the fire. Factors to be considered in the loading-out method are (1) availability of a disposal site for excavated material, (2) the nature of overburden, (3) a sufficient supply of water, and (4) the presence of surface improvements. In this method, the recovery of coal may reduce the total cost.

Inundation

Inundation methods involve the underground use of water to lower the temperature of the burning material. Flooding and continuous pumping are two techniques for inundation.

In flooding, dams are constructed underground to raise the normal water level above that of the burning material. This method has had very limited use. Flooding has been effective only with relatively small fires in sections of active mines that were below the water table. However, it is dangerous, costly, and, at times, impossible to erect dams in inaccessible areas or where strata are not competent to withstand the additional hydrostatic pressure. Geological and physical conditions often make the emplacement of an effective dam unlikely. Confining water for complete inundation is almost impossible near outcrops or along anticlines. The practical difficulties in confining water in a safe manner have limited the use of this method of mine fire control.

Another inundation method is the continuous pumping of water over and through the burning material. Although this method has the advantage of being applied from a surface location, it has not been attempted on a large scale. In general, the volume of water required, the cost of the high-capacity pumps needed, and the length of time pumping would have to be continued have limited consideration of this method. The primary technical drawback to this method is the possibility that the water will run in channels and not cool the entire fire zone. If the water bypasses some of the burning material, there is a possibility that isolated hot areas will remain and eventually reignite the fire after pumping is stopped.

Flushing

Flushing is designed to fill the voids in an underground fire with fine noncombustible solids. This is accomplished by injecting a slurry of water and noncombustible material into the mine voids through boreholes. The noncombustible material is expected to fill mine voids and interstices in the surrounding strata, and thereby extinguish or limit the propagation of the fire by sealing the area and preventing air from reaching the burning coal. In addition to carrying the noncombustible material, the water also serves to remove heat from the fire area.

Flushing can be effective where deposition can be controlled, where voids have a relatively simple geometry, and where the injected material will remain in place. However, in flushing, an adequate seal is often difficult to achieve. Frequently, interstices and crevices of relaxed strata are not filled. It is difficult to emplace a complete seal in rubblized areas and in steeply pitching seams; the natural tendency of flushing is to carry material downdip to some indeterminable point. Even if a complete seal is emplaced originally, gravity may eventually cause the material to settle or slump, and drying may cause the material to shrink and crack. A recent adaptation to flushing hydraulically is the use of air to inject or blow noncombustibles into mine voids (sometimes referred to as pneumatic injection). This technique will generally decrease the amount of shrinkage and runoff of noncombustibles in the voids, but suffers the disadvantage of adding oxygen to the underground fire zones. The latter disadvantage could be eliminated by using inert gas rather than air in the injection process.

Fire Barriers

A fire barrier is a noncombustible dam placed between the fire and the contiguous coal. The barrier breaks the continuity of all coal and carbonaceous shales and must be wide enough to prevent heat transfer from the fire side to the cold side. The barrier used to isolate a fire can be a trench barrier, tunnel barrier, or plug barrier.

A trench barrier is installed by excavating an open trench between the fire area and the threatened area. To confine the fire, the trench extends vertically from the surface to the bottom of the coalbed, and horizontally from outcrop to outcrop or to water level. A minimum width of 12 feet at the bottom of the trench has been considered essential (6). Even though the trench is backfilled with noncombustible material, the extent of surface disruption is a serious factor in the feasibility of a trench. Also, the location of the trench must be such that all of the fire is contained on one side of it.

A tunnel barrier is an underground tunnel backfilled with noncombustible material. It is usually used to extend a fire barrier when the depth is too great to excavate from the surface. Generally, the tunnel is backfilled with coarse material; then holes are drilled from the surface, and finely divided material is injected to fill all voids and interstices to create a barrier.

A plug barrier may be a trench, tunnel, or a combination of both. It is referred to as a plug because it does not extend to the opposite outcrop. With horizontal coal seams (e.g., Pittsburgh bituminous), a plug barrier generally terminates under more than 60 feet of cover, in flooded workings, or in solid coal. The criterion of 60 feet of cover is intended to prevent the burning bed from fracturing shallow strata, permitting air to reach the fire. However, under some circumstances even this depth may not be adequate.

Surface Sealing

Surface sealing is a relatively inexpensive method of mine fire control that is intended to inhibit ventilation of the fire zone, excluding air and smothering the fire by the accumulation of combustion gases. In practice, this is quite difficult. The seal of noncombustible material must be packed 8 to 10 feet thick over the fire area. It must be maintained at this thickness over a period of time sufficient for the slow dissipation of heat. If a good seal is maintained over a sufficient period of time, the fire is smothered in an oxygen-deficient atmosphere and the temperature is lowered below ignition temperature. This method is generally used on fires under shallow cover where a quick and inexpensive remedial action is desired. Two methods have been used to construct a surface seal: One creates a seal by plowing the surface to a pulverized condition, and the other creates a seal by depositing suitable material on the surface over the fire.

To date, in small sections of active mines, inundation and stripping or digging out have been the most successful methods of extinguishing underground fires. Flushing and sealing are used to retard or control the spread of a fire. Of the methods used to control underground mine fires, only excavation has been successful in more than 50 pct of the projects in which it was used. In addition to the technical limitations inherent in the various fire control methods, economics must be considered a major factor in determining the success of a fire control project. In some cases, a fire control project may have been successful if pursued to completion rather than terminated when allotted funds were expended.

FACTORS AFFECTING THE BEHAVIOR OF ANTHRACITE MINE FIRES

Fires in the Anthracite Region have been greatly affected by the geological structure of the area, the past mining, and the nature of the coal itself. The particular conditions in this region of the country have made fire control much more difficult than is the general rule in bituminous coal-mining areas.

Geology

Geologic factors that affect the propagation of anthracite mine fires are the dip or pitch of the beds, the number of coalbeds in the stratigraphic section, and the competency of the overlying rocks. An important geological factor in both the spread of an anthracite mine fire and the difficulty of extinguishing it is the steep pitch of the coalbeds (40° to 80° pitch). In controlling a fire in an essentially flat-lying coalbed, noncombustible material can be pumped into mine voids to form a barrier, sealing off the fire area. Because of the steep pitch of the anthracite beds, this technique is generally ineffective since anything pumped into the coalbed from the surface flows downdip, requiring indeterminable quantities to provide a seal.

The pitch of the bed plays an important role in ventilation of fire areas, perhaps the most important factor in the propagation of fires. On steep pitches, differences in temperature and elevation are sufficient to establish the circulation of air and fumes. The movement of hot gases is an important factor in the transfer of heat generated by the fire. This transfer may influence both propagation of the fire and dissipation of the heat generated by the fire. Such circulation may set up self-propagating convection cells, which could explain the propagation of the fire to unexpected depths and areas. A fire at the outcrop of a steeply dipping mined bed has an "open stack" to the surface, and the draft that is set up can draw fresh air from within the mine, causing the fire to propagate downdip. The development of ventilation patterns related to the pitch of the coalbed is theorized from observations on the propagation of anthracite mine fires. Sufficient data on relationships between temperature, pressure, and elevation in the fire area are not available to more accurately describe underground ventilation patterns in mine fire areas.

In addition to the pitch, the intense folding and faulting in this region have contributed to subsidence fractures extending from the coalbed to the surface as well as between coalbeds. These cracks provide a ready supply of oxygen to the fire underground, and allow the migration of hot gases from the fire to overlying coalbeds. The number of coalbeds and the distance between them are also factors in the control of anthracite mine fires. Given sufficient time and proper conditions, it is generally expected that a fire in one coalbed will spread to coalbeds above it. The rate of propagation may be a function of the temperature of the combustion gases as they move upward and/or the heat conductivity of the strata between the coalbeds. Again, the fact that anthracite mine fires can spread to overlying coalbeds is known, but the exact mechanism of such propagation has not been determined.

Previous Mining

Another important factor in the spread of anthracite fires is the great extent to which this region has been deep mined. In many instances, a mine was returned to and worked a second time or even "third-mined," where the coal pillars left to support the mine were removed, creating a gob or rubblized area. In these third-mined areas, the gob has a relatively large surface area, making the fragmented coal more readily combustible than solid coal. Also, these gob areas are heterogeneous so that they have a variable permeability to air and water; it is very difficult to seal and/or flush such areas.

Whereas fires in accessible workings can be attacked directly and readily extinguished, fires in previously mined areas are often in caved and virtually inaccessible areas, where direct attack by underground personnel often fails to extinguish the fire. The records examined by McElroy show many instances of fires that were considered extinguished, but that recurred after intervals of weeks, months, or years. In many cases, affected areas were sealed off. The only available evidence of the progress of fires is what can be determined from indirect observations made by drilling or secondary indications at remote points. This makes it difficult to determine with absolute certainty whether or not such fires have actually been extinguished.

Previous mining is also significant because of the role it plays in providing ventilation to the fire area. Open passageways and rubblized areas allow circulation of air underground, which may lead to the formation of convection cells in which air is drawn into the fire at one point and combustion gases are exhausted at another. In areas where mining has occurred, particularly multiple-seam mining, as is common in the Anthracite Region, caving often results in subsidence cracks and sinkholes in the overburden through which oxygen is supplied to the fire. The McElroy study of mine fire behavior patterns in active mines showed that nearly all of the costly and dangerous recurrences of fires have been in second-mined and caved areas extending to the surface or to the saddles of anticlines. Although the caved ground and surface soil appear to be compact, they are essentially permeable to air, and large openings may exist in the broken strata over anticlines. Therefore, fires in areas breached to the surface or under anticlines have an open top. Air circulation to a fire at any depth can be produced by natural ventilation currents set up by the heat of the burning material and variations in gas densities. The airflow is to and from the surface or adjacent areas; even in the "sealed" areas convection currents may cause recirculation.

Natural circulation also influences the direction in which the fires propagate. Where the air supply is small, extinctive gases generated by the fire accumulate above it and hinder propagation up the pitch. The gases also limit lateral propagation to some extent. However, the bottom of the fire area receives the purest air and burns the strongest. Therefore, in caved areas, the fastest rate of propagation is usually down the pitch, or toward the source of air. If the air supply is abundant, the fire spreads rapidly both up the pitch and laterally.

In caved areas, the fineness of the broken material and the relative amount of open space are important elements in determining the behavior of the fire. Near the surface and in thick seams or closely spaced seams, the caved ground is comparatively open, and fires spread rapidly up the pitch and laterally along the strike, and at the same time fairly rapidly down the pitch. At greater depths and in thin seams, the fire spreads more slowly down the pitch and laterally. In some cases, the ground is so compact that the fire apparently barely exists after the ground has settled following pillar mining and only becomes active when the ground is again disturbed.

The history of mining in the area has also played a role in the spread of fires (3). Following World War II, the drastic decline in the demand for anthracite resulted in the abandonment of deep mining operations due to rising costs. Consequently, many operators turned to stripping operations, a cheaper alternative. These stripping pits were eventually abandoned, leaving an exposed coal outcrop. Because these pits presented a natural disposal area, trash was deposited there, and fires that started from burning trash soon spread along the outcrop to the interconnected multiple-seam underground workings that had been abandoned earlier. As a result of this progression of events, the incidence of anthracite mine fires has increased in the past 30 years.

Characteristics of Anthracite

Several factors that have contributed to the propagation of anthracite mine fires are related to the properties of the coal itself. From McElroy's study, it is apparent that fires can exist for as long as 15 to 25 years with no surface indications and become ragingly active in a very short time after the ground is disturbed by pillar mining in the seam below. The two main factors thought to be involved are the low heat conductivities of the materials and the "conditioning" of the materials by prolonged heating.

Anthracite, either solid or finely divided, has low heat conductivity, about one-tenth that of igneous rocks. The adjacent materials, usually slates, also have low heat values. Consequently, the intense heat generated by a fire is not readily absorbed and dissipated through the surrounding material. In an active mine, when a fire originated in a pillar-mined area on a steep pitch, the initial fire-fighting methods were sealing, with or without flushing, and covering of breaches, to materially reduce the supply of air and limit both the intensity and size of the fire. With tight seals and rather open ground, there may be sufficient air circulation to convey heat away from the fire, and extinguish it in time. Most of the heat loss in a mine fire is by convection rather than conduction.

If the fires are in compact ground, where the air currents are sluggish, heat transfer by conduction occurs at too low a rate to reduce the temperature of the burning mass below the point of reignition. Fires may continue to burn indefinitely in local areas, with the rate of burning depending on the combustible content and the availability of oxygen. Hot gases rising from such dormant fire areas may pass so slowly to the surface that their temperature is reduced. At the surface, combustion gases are diffused and go undetected. Such fires, burning in small isolated areas or merely oxidizing at a high rate, generate sufficient heat to maintain a temperature that permits reignition when sufficient air is available.

Thus, once a fire has become deep seated, its stored thermal energy is a potential heat source for fire propagation for many years, even when the supply of oxygen is limited. The low thermal conductivity of the coal and the surrounding strata serve to insulate the fire zone and retard the cooling of the hot material.

The fact that dormant fires can become active very quickly was attributed by McElroy to the "conditioning" of materials in the fire area by long-continued heating at relatively low temperatures. The author postulated that this conditioning effect was due to the driving off of some of the water in the coal, its partial heating, and possibly the absorption of oxygen and other gases.

This conditioning in fire areas is particularly applicable when fines are flushed into fire areas to construct air seals. Many fires that are supposedly extinguished by flushing recur when the area is disturbed. In these cases, flushing probably extinguishes the fire over large areas, but locally, burning masses could be insulated by consolidated fines, keeping the fire burning at low intensity over a long period. The surrounding material become conditioned, so that when movement causes cracks in the consolidated fines and air reaches the fire, the prepared material burns freely and generates an intense fire in a very short time.

This opinion is consistent with laboratory data on the low-temperature oxidation of anthracite. Figure 5 is a plot of anthracite oxidation, from data reported by Scott (22), which shows that acceleration of the reaction starts in the temperature region of 80° to 120° C (176° to 248° F), depending to some extent on the amount of prior oxidation. Similar data have been obtained in recent studies with bituminous coals at the Pittsburgh Research Center (11). With bituminous coals, the reaction accelerates at temperatures as low as 120° to 160° F.

From the above, a mechanism of fire propagation is postulated that involves local spontaneous ignitions in areas that

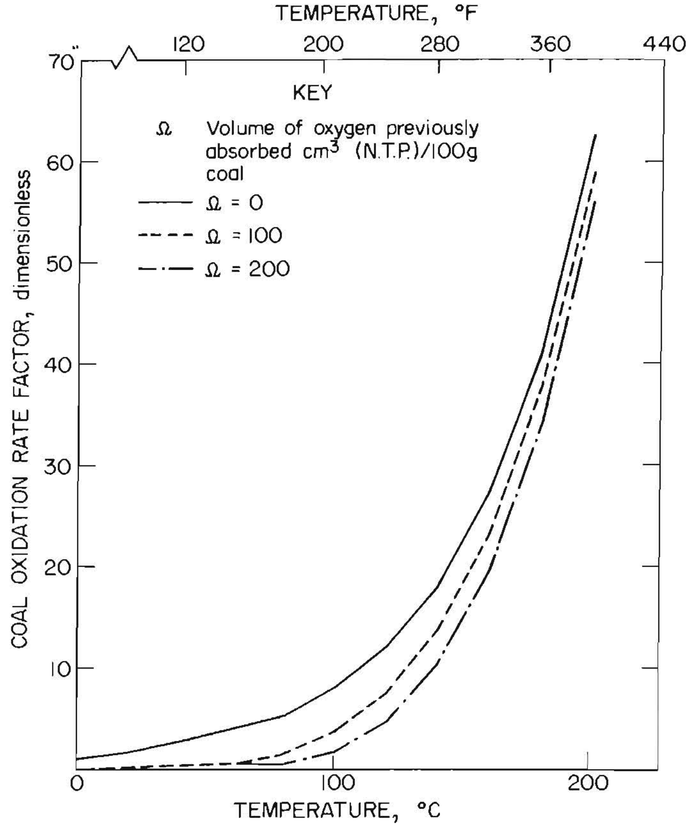

FIGURE 5. - Plot of anthracite oxidation rate vs temperature (based on data from Scott 22).

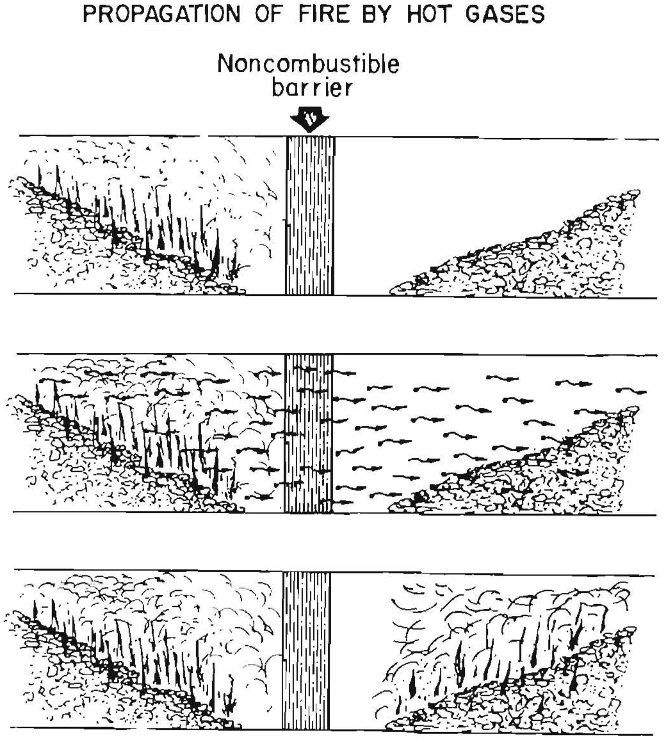

FIGURE 6. - Postulated spread of combustion by hot gases.

have been preheated or conditioned. The thermal energy for this process is from a source of heat (i.e., fire zone), which may be far removed from the site of the spontaneous ignition (fig. 6). This is in contrast to a flame-spread mechanism where coal adjacent to a burning area is heated, primarily by conduction and radiation to its ignition temperature of approximately 900° F.

The theory of low-temperature conditioning and spontaneous ignition could be a factor in the apparently discontinuous spread of some anthracite fires. For example, a fire occurs in some workings near an outcrop. The fire induces circulating air currents, which carry fumes and heat into the interior of the mine, both laterally and to lower depths. The effective ambient temperature of a large area of the mine is slowly increased. At temperatures approaching 200° F, the anthracite is conditioned by drying, leading to accelerated oxidation reactions in local regions where oxygen is present. If in these same local regions the heat is not readily dissipated, spontaneous heating will occur resulting in ignition of the coal to flaming combustion. Local conditions of temperature, oxygen availability, and heat dissipation will determine whether or not a given small section of areas heated to 200° F in the mine will eventually undergo spontaneous heating to ignition.

Thus, it is possible that after a period of time, the outcrop fire gives rise to several fires in the workings, which can be far displaced from the original fire site. In turn, each local fire can be the source of heat for other localized spontaneous heatings, as well as a new energy and gas source for inducing recirculation flows in the mine entries. To extinguish mine fires, the temperatures should be below 200° F before seals are broken and air is permited to enter the area known to have been on fire. It is possible that fire would be reactivated if air were admitted into an area having temperatures above 200° F. Although ignition temperature of anthracite range from 815° to 878° F, a fire cannot be considered extinguished until all temperatures in the fire area are below 200° F.

In addition to the low heat conductivity of anthracite and the process of conditioning, McElroy speculated that the propagation of anthracite mine fires was related to the production of hydrogen from the heated coal. A characteristic of the combustion of anthracite is the amount of hydrogen gas given off by high-temperature distillation. Above about 1,100° F (red heat), approximately three-quarters of the gas produced is hydrogen. Hydrogen is a light gas (density about one-fifteenth that of air) with wide explosive limits (4 to 74 pct in air). Large quantities may be generated by heating anthracite in the absence of air. If hydrogen accumulated in openings above an active fire area, exploding or burning of hydrogen-air mixtures could communicate fires long distances through openings in the strata, or along saddles of anticlines and along barrier pillars. The production, migration, and combustion of hydrogen may also transmit fires through noncombustible barriers.

The ability of anthracite to absorb gases is also considered a factor in the persistence and propagation of fires in this region. Since anthracite is known to absorb gases, particularly carbon dioxide, it is possible that it may absorb some of the fumes from fire areas. Thus, air currents migrating a long distance from fire areas may lack detectable combustion gases. Also fire fumes and gases cool as they rise through the ground, both by contact with cooler rock and air and by slight decompression due to change in elevation. Components of fire fumes, which are responsible for odors, can be condensed out as they move through the ground. Therefore, air from fire areas may not contain detectable smoke, and even very low amounts of carbon dioxide may be significant.

ASSESSMENT OF FIRE CONTROL EFFORTS IN THE ANTHRACITE REGION

In this section, the effectiveness of past fire control efforts in this region are evaluated, based on conclusions drawn from the McElroy study of active mine fires and an examination of the abandoned mine fire control projects conducted by the Bureau.

McElroy gathered data on 103 major fires and 71 minor fires that occurred in Pennsylvania active anthracite mines between 1850 and 1936 (13). Although only limited written information was available, he consulted with mine officials familiar with the fires in order to assess costs, causes, and factors affecting propagation and control.

All the fires described by McElroy had occurred in the Western Middle and Southern Fields of the Pennsylvania Anthracite Region in a large group of steep-pitch mines. The anthracite occurred as a series of up to 20 parallel seams in folded slate and sandstone strata on pitches of 40° to 80°, with vein thickness of 5 to 6 feet. Practically all were old mines with operations at that time either under or adjacent to mined-out areas extending to the surface or to the saddles of anticlines. All operations were at relatively shallow depths, that is, within 1,000 feet of the surface.

In the group of fires studied, the cause of the fire was either known or the most probable cause assigned. For the 103 major fires tabulated by McElroy, 17 fires were caused by gas ignitions and explosions. The cause of 30 of the fires was related to the use of explosives. Other primary causes included open lights, surface fires, smoking, and electricity. Twenty-two of the fires were recurrences of older fires. With respect to intensity of the fire, difficulty in controlling it and total costs, recurrences of old fires constituted the major problem. It was considered possible that some fires that were believed extinguished had continued to burn undetected for 15 to 25 years. In other instances, a supposedly extinguished fire was considered the source of a new fire in the same vicinity, even though no direct path between the two fires could be found. Chemical, physical, geological, and mining factors were thought to make complete control of such fires especially difficult.

It was observed that the ineffective methods used to control or extinguish anthracite mine fires in their initial stages usually led to prolonged and expensive efforts. The success of methods to control and extinguish fires on steep pitches in caved areas depends upon local conditions, the extent of the fires, and the time elapsed before control measures are applied. At the time of McElroy's study, there were three general methods of extinguishing fires in active mines: direct attack, sealing the area containing the fire, and flooding the area. Practically all fires that are discovered soon after they start can be extinguished by direct attack by underground personnel. Those that require other methods are usually those that have burned undetected in second-mined areas. Direct methods include spraying the fire with water, using chemical extinguishers and excavating and quenching the burning material. According to McElroy, direct methods are considered applicable only to relatively small, accessible fires, and not when the extent of the fire area is uncertain or when the fire is in a caved area. In such cases, sealing or flooding the fire area is thought to be more effective.

Sealing the area containing the fire has been only moderately successful in the Western Middle and Southern Anthracite Fields. The steeply pitching parallel seams occur in hard rock strata that have been folded and faulted; they have been mined to considerable depths without backfilling, and they are breached or caved to the surface along all outcrops. The sealing of the fire areas is almost uniformly ineffective, except to retard the rate of combustion. Lack of an effective seal over caved areas at the surface is probably the most important factor. Passage of air from adjacent seams through joint planes and cracks in the divider rock, and through broken strata over anticlines is also a factor. For sealing to be effective, the seals must be tight enough to prevent the admission of air to the sealed area, so that the fire will consume the available oxygen until it is reduced to a concentration that will not support combustion or rapid oxidation. The atmosphere must then be held in that state until the temperature of the partly burned material falls below the temperature at which it will reignite when the area is opened.

Usually, the greatest difficulty in extinguishing fires by sealing is the "breathing" of sealed areas due to changes in barometric pressure. The volume of air in such spaces tends to change inversely with the change in barometric pressure, alternately putting pressure (decreasing barometric pressure) and suction (increasing barometric pressure) on the seals. If the seals are absolutely tight, atmospheric pressure changes will be exerted on them uniformly, and the volume within the enclosed area will remain unchanged. Leaks act to reduce the pressure differences on seals by allowing volume changes within the enclosed area. Where the leakage paths connect to ventilated areas, air inflow to the sealed area sometimes prevents the lowering of the oxygen content.

Fires or heated masses in inclined workings generate pressure by temperature differences, causing air to circulate. In a sealed fire area, recirculation within the seals tends to maintain a uniform gas mixture, promotes the rapid reduction of the oxygen content, and aids in the dissipation of heat. In partly sealed areas, natural draft pressures cause recirculation within the area and cause leakage through seals, cracks in the strata, and caved ground.

Natural drafts tend to cause suction on the lower seals and pressure on the upper seals. If only normal atmospheres are involved, natural draft pressures on seals can be estimated as approximately 0.03-inch water gage per 10° F difference in temperature per 100-foot difference in elevation. However, usually the seals are so remote from the fire that temperatures are equalized, and the pressure effects are due largely to differences in densities between the air-gas mixture within the area and the air without, and the pressure differential generated could be 0.3 inch water per 100-foot difference in elevation.

Pressures on seals are usually due to variations in barometric pressure, temperature, air and gas composition, mechanical and natural drafts, and leakage. They are also due to the expansion and contraction of the enclosed atmosphere and to increased volumes caused by gases (methane) released from the strata. Often, pressures on the seals must be released to prevent failure. High pressures, except in the special case of gas outbursts within the affected area, usually denote tight sealing.

Effectively sealing surface areas is extremely difficult. The difficulties are related primarily to the lack of a suitable sealing material, a relatively thin layer of which would form an airtight seal, and to the inability to locate all surface openings. Clay seal volumes decrease with drying, and to be effective, clay seals have to be kept wet.

Even if a fire area can be adequately sealed, the time required to completely extinguish a fire is considered to be at least several years. After the fire is extinguished, masses of heated material must be cooled to a temperature below that required for reignition. In a sealed area with voids for circulation of natural draft currents, the temperature can be reduced within a relatively short time. When there is little void space and the heat must be dissipated through poorly conducting materials, the recurrence of a fire, when a sealed area is opened, is considered more probable.

Flushing and flooding the fire area is the other method used to control and/or extinguish the underground anthracite fires. Flushing is essentially a method of flooding with a slurry of solid material instead of water alone. In the anthracite fires studied by McElroy, the solid material used was fine culm (waste coal and rock); noncombustibles, such as sand or clay, were generally considered to be too expensive for use. As a method to extinguish fires, flushing was only 50 pct successful; its primary effect was to retard the extension of fires. Because of the amount of water used, some of the successfully flushed fires actually may have been extinguished by flooding.

As a means of retarding the extension of fires, flushing is generally more effective than sealing. The water by which the slurry is introduced has sufficient heat capacity to quench fires in large areas and dissipate heat. After drying, the slurry surrounds and insulates the burning material, filling the voids and reducing the flow of air to the burning material. Flushing appears to be an adequate method of retarding combustion, and it probably is the most effective method for making a seal in broken ground and in otherwise inaccessible openings.

Flooding was the most generally successful method used in the cases studied by McElroy. Where the water reaches a level above the fire, flooding is successful. Failures primarily are due to not allowing the area to remain flooded long enough for fires in dead ends to consume the oxygen of trapped and compressed air, and to the inability to flood burning areas to the highest levels the fire might have reached. In any extensive workings that are flooded, there are local dead ends in which the rising water will trap air and compress it. An outlet for the air from large dead-ended sections can be provided, but many small ones cannot be detected. It is therefore necessary to allow sufficient time for even a small fire to consume the oxygen and die out.

In some flooding attempts, maximum height of the fire is estimated as the known upper extent of the fire area before flooding. This does not take into account the possibility that the air and gases forced upward through small openings by the rising waters may have caused a rapid extension of the fire area up the pitch to points above the highest level the water attained.

When the fire is in caved workings that extend to the surface, it is not possible to flood the entire area; the water will run off at some point below the highest elevation occupied by the caved material. Fire in areas above water must be extinguished by some other method, or the fire will extend down the pitch when the area is dewatered. The only certain method of handling areas above water level has been to dig them out or remove the material by stripping. Based on the fires studied by McElroy, flooding and stripping are considered the most effective methods for controlling and/or extinguishing fires extending to the surface. Although the cost is high, some commercial coal is recovered.

In more recent fire control projects, the control methods most often used have been excavation, trenching, and flushing. Since 1950, the Bureau of Mines has been involved in 26 mine fire control projects at 17 abandoned mine sites (including Centralia) in the Pennsylvania Anthracite Region. The history of each of these fire projects was reviewed to assess the various control methods and their relative effectiveness. These projects are summarized in table 1.

Five of the fire sites involved 14 separate fire control projects. This was due to the fact that repeated attempts were made before the fire was successfully controlled. At the four sites other than Centralia, the fire was finally extinguished by complete excavation. Of the 12 sites at which only one attempt was made to control the fire, 11 were successfully controlled and 1 was not.

A summary of cost-data and effectiveness for all the projects examined (table 2) leads to some interesting observations. While the number of cases is not sufficient for rigorous statistical analysis, several significant points are apparent:

1. Only slightly more than 50 pct of the fire control projects were successful in controlling or extinguishing the fire.

2. Excavation was the most successful control method (8 out of 10 trials).

3. Flushing (with or without partial excavation) was successful for only about half of the attempts. This is about the same success rate as reported by McElroy in his report on pre-1938 anthracite mine fires. Only one of the successful flushing projects was in the Western Middle Field, but three of the eight unsuccessful flushing projects were.

4. Approximately $37 million was spent on successful projects, and approximately $6 million was spent on unsuccessful projects. On a per fire basis, success is 5 times more costly than failure.

5. In scrutinizing the actual fire histories, it is apparent that the fire projects started with insufficient funds required repeated efforts. While financial and engineering arrangements for repeat projects were being made (taking several years in some cases), the fire often spread and became more difficult and more costly to control. The history of the Centralia mine fire is typical (see section, "Centralia Mine Fire").

TABLE 1. - Summary of anthracite mine fire projects since 1950

Site	Year	Anthracite field (pitch)	Approx. acreage	Control method	Expenditure, dollars	Result
Shamokin Mine..	1950-1951	W. Middle (steep)	7	Surface seal.............	5,101	Successful.
Kulpmont Mine..	1950	W. Middle (20°)..	30	Trench and backfill.......	94,425	Unsuccessful.
	1958	W. Middle (20°)..	(1)	Partial stripping.........		Do.
	1960	W. Middle (20°)..	(1)	Trench to water level, stripping.	85,237	Successful.
Mt. Carmel.....	1950	W. Middle (40°)..	170	Surface sealing...........	76,664	Unsuccessful.
	1952	W. Middle (40°)..	(1)	Surface sealing, flushing.	229,603	Do.
	1967	W. Middle (40°)..	(1)	Complete excavation.......	7,962,183	Successful.
Carbondale.....	1950	Northern (-).....	250	Flushing..................	475,000	Unsuccessful.
	1974	Northern (-).....	(1)	Complete excavation.......	6,125,000	Successful.
Tower City Mine	1952-1954	Southern (steep).	6	Blasting, flushing, stripping.	241,298	Do.
N. Scranton....	1960	Northern (14°)...	23	Flushing with sand........	443,500	Do.
Cedar Avenue...	1953	Northern (10°)...	34	Excavation, flushing......	373,850	Unsuccessful.
	1962-1965	Northern (10°)...	34	Flushing..................	774,610	Do
	1968-1973	Northern (10°)...	(1)	Complete excavation.......	4,355,602	Successful.
Laurel Run.....	1966-1971	Northern (60°)...	(1)	Flush isolation barrier, excavation.	1,336,175	Successful (isolation).
Coal Run Mine..	1962-1963	W. Middle (25°)..	100	Trenching, flushing.......	196,226	Do.
Eynon Street...	1965	Northern (-).....	5	Flushing..................	296,940	Successful.
Warrior Run....	1968-1971	Northern (28°)...	18	Fly ash and sand barrier, excavation.	732,818	Unsuccessful.
Kehley Run.....	1969	W. Middle (steep)	(1)	Complete excavation.......	11,681,585	Successful.
Hazelton.......	1969	E. Middle (55°)..	8	.....do..................	1,445,602	Do.
Swoyersville...	1969-1973	Northern (65°)...	8	.....do..................	785,418	Do.
Throop.........	1968	Northern (20°)...	7	.....do..................	762,573	Do.
Eddy Creek.....	1974	Northern (-).....	48	Flushing..................	1,652,444	Do.
Centralia......	1966	W. Middle (40°)..	9	Flushing, excavation......	326,123	Unsuccessful.
	1968-1974	W. Middle (40°)..	(1)	Fly ash isolation barrier.	2,441,084	Do.
	1978	W. Middle (40°)..	300	Reinforce fly ash barrier.	498,278	Do.

[1] No information available; actual acreage not reported.

TABLE 2. - Effectiveness of anthracite mine fire projects since 1950

Method	Successful		Unsuccessful	
	No.	Cost, thousands	No.	Cost, thousands
Surface sealing	1	$5	1	$77
Flushing or injection (w/wo excavation)	6	4,166	8	5,852
Excavation	8	33,203	2	94
Total	15	37,374	11	6,023
Average cost per fire	NAp	2,492	NAp	548

In assessing Bureau of Mines abandoned mine fire control projects, it is clear that complete excavation is the one positive approach that has a high probability of success. Although flushing has occasionally been successful, as McElroy pointed out, it requires extreme care in injection of slurry, and results must be monitored to insure the adequacy of the flushing operation. Surface sealing is considered only when the area to be sealed and the funds available are very limited. There is very little indication that underground tunnel barriers are successful in containing a fire, and may only serve to retard the fire and change the direction of propagation.

EFFECTS OF ANTHRACITE MINE FIRES

Mine fires in the Anthracite Region have destroyed remaining coal reserves, resulted in surface subsidence, and caused active mining operations nearby to be closed down. However, the most serious problem caused by most mine fires in the region is not the possibility of fire or subsidence in the community, but the presence of hazardous combustion gases which have migrated into area homes through fractures in the strata overlying the fire. In this region, many towns and cities overlie abandoned underground workings. Although there is little risk of fire on the surface, the gases from the fire are a serious hazard to public health and safety. These gases can accumulate in closed, unventilated areas such as basements and closets. For the most part, the hazards are relatively low, and normal ventilation will dissipate any gases that may seep into area homes. These gases may include carbon monoxide (CO), which is potentially lethal, and there is also a possibility that slightly elevated levels of carbon dioxide (CO_2) or deficiency of oxygen (O_2) could cause some physical effects with prolonged exposure.

Carbon monoxide is the most serious hazard for homes in the area of a fire. This colorless, odorless gas readily combines with the hemoglobin of the blood, replacing the oxygen normally carried and resulting in respiratory failure if the CO concentration is high enough. The effects at lower levels range from a slight headache at 10 to 20 pct saturation of hemoglobin as carboxyhemoglobin in the blood to severe headache, dizziness, faintness, impaired motor coordination, nausea, and vomiting at levels up to 40 pct. From 40 to 70 pct, the symptoms progress from increased respiration and pulse rate to collapse, coma, and convulsions. Respiratory failure and death generally occur at levels of 70 to 80 pct.

The threshold limit value[7] of 100 ppm had been generally accepted for many years (14), but more recent estimates have placed it at 50 ppm (1, 15), a level which will result in a value of 8 to 10 pct carboxyhemoglobin. The recommended occupational exposure as determined by National Institute for Occupational Safety and Health (NIOSH) is 35 ppm for an 8-hour workday (24). The effect of the CO concentration increases with longer duration of exposure, higher humidity, and lower barometric pressure. The rate of the effect also increases with the degree of physical exertion. Other conditions that increase the effect are old age, youth, pregnancy, heart disease, poor circulation, anemia, asthma, lung impairment, or presence of alcohol or drugs in the blood.

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[7] A threshold limit value (TLV) is a time-weighted average concentration of a substance in the air to which nearly all workers may be exposed without adverse effects for a normal 8-hour workday or 40-hour workweek, for an indefinite period.

In addition to the CO, a fire also can cause somewhat increased levels of CO_2 and decreased levels of oxygen. The normal concentration of CO_2 in the atmosphere is 0.03 pct. The threshold limit value for an 8-hour daily exposure to CO_2 has been set at 5,000 ppm or 0.5 pct of the atmosphere, provided the percentage of oxygen is normal (1, 14-15). The recommended occupational exposure as determined by NIOSH is 10,000 ppm or 1 pct CO_2 by volume for a 10-hour shift in a 40-hour workweek (25).

The studies conducted by NIOSH (25) show that during prolonged exposure to slightly elevated CO_2 concentration (1 to 3 pct), the body generally can adapt to this chemical imbalance and restore homeostasis (an acceptable equilibrium). Under normal conditions, the CO_2 carried by the blood to the lungs is readily exchanged for oxygen since the partial pressure of CO_2 in the blood is greater than the CO_2 pressure in the air in the lungs; the CO_2 moves readily to the area of less pressure. If the air breathed has a higher pressure because it contains a higher concentration of CO_2, less CO_2 will be exchanged in the lungs, thus increasing the level of CO_2 in the blood. The dissolved CO_2 in the blood routinely undergoes hydration, producing hydrogen and bicarbonate ions. If the CO_2 level of the blood is higher than normal, the level of hydrogen and bicarbonate ions produced also increases, resulting in respiratory acidosis, an excess of acid in the body.

When acidosis occurs, the body can restore homeostasis through two compensatory mechanisms: increased ventilation rate, which helps to stabilize the CO_2 level by increasing the CO_2 eliminated by the lungs, and renal mechanisms, which help to restore the acid-base balance through excretion of the excess bicarbonate and hydrogen ions.

Studies have shown that although chronic exposure to CO_2 concentrations of 0.9 to 1.9 pct did result in retention of CO_2 in the body and resultant acidosis, the body generally is able to restore normal pH through the pulmonary and renal mechanisms (25). In these studies, increased CO_2 levels were observed for as long as 42 days. In studies of intermittent exposure, where the subjects returned to normal air for short periods, the developed patterns of compensation were not altered by the interruption.

Generally, the pulmonary response (increased breathing rate) is immediate. The renal response is somewhat delayed and appears to be dependent on the degree of the CO_2 concentration. At low levels, the body took as long as 3 weeks to trigger the renal response, but in a study using 1.5 pct CO_2 concentrations with constant exposure, the response was triggered in 3 days.

Another effect observed was a loss of efficiency in performing physical exercise after prolonged exposure to 2 pct CO_2. Studies using up to 3 pct CO_2 showed no effect on problem-solving or eye-hand coordination.

Prolonged exposure to slightly decreased levels of oxygen has much the same effect as a slight increase of CO_2 concentration. The CO_2-O_2 exchange in the lungs is disturbed since the decreased concentration of oxygen in the air breathed means that less oxygen is absorbed by the blood, resulting in an excess of CO_2, and acidosis.

The normal oxygen concentration in the air is 20.95 pct. Acidosis will occur after chronic exposure at concentrations of 17.5 to 19 pct. If the oxygen concentration decreases to 16 pct, symptoms of anoxia or oxygen deficiency begin to appear. These effects include increased breathing and pulse rates at 12 to 16 pct; abnormal fatigue and disturbed respiration at 10-17 pct; nausea, vomiting, and loss of consciousness at 6 to 10 pct; and convulsions and respiratory failure at concentrations under 6 pct. For persons with cardiac or pulmonary problems or a hyperthyroid condition, the effects of oxygen deficiency are more severe.

Although the concentrations of combustion gases have rarely reached harmful levels, the possibility of hazardous emissions is a serious problem for residents in fire areas.

CONCLUSIONS

From the in-depth study of past mine fires and fire control efforts in the Anthracite Region, some basic conclusions can be drawn:

1. Fires in steeply pitching anthracite workings are difficult to extinguish and may burn undetected for very long periods of time.

2. Natural ventilation in sealed fire areas influences the direction and extent of the fire propagation.

3. In sealed areas of active mines with rather fractured ground, air currents can serve to dissipate heat and lower the temperature of the material in the area.

4 Caved areas, which are essentially open to the surface, allow circulation of air to the underground fire and are extremely difficult to seal.

5. In some areas, smoldering combustion will provide sufficient heat to maintain a temperature that will ignite volatiles whenever air is available.

6. Since the low heat conductivity of anthracite results in retention of heat, "conditioning" or drying of the coal by prolonged heating at 200° F can produce spontaneous combustion in now dormant areas. Therefore, a fire cannot be considered extinguished until all temperatures in the fire area are below 200° F.

7. Natural ventilation, even in sealed areas, can transfer heat beyond barriers and provide the oxygen which can trigger reignition, possibly at temperatures as low as 200° F when the coal has been "conditioned." This results in the propagation of the fire to unexpected depths and areas.

8. Hydrogen produced by the burning anthracite may migrate through barriers and explode if an ignition source is present, causing the outbreak of fire beyond the barrier.

9. In active mines, direct attack is an effective method of controlling only relatively small, accessible fires.

10. Excavation has been the most successful fire control method in the Anthracite Region.

11. Flooding has been effective when a fire is in a section of an active mine below the level of the water table.

12. Air sealing was generally ineffective in controlling fires in the Anthracite Region because the highly faulted strata and subsidence due to mining make it virtually impossible to maintain a tight seal.

13. Even if an area could be completely sealed, the seal must be maintained for several years for the fire to be completely extinguished and for the burning material to cool below the reignition point.

14. Flushing in anthracite areas is limited by the steep pitch of the coalbeds, which makes it difficult to completely fill mine voids.

15. Materials injected into an area to extinguish a fire may actually insulate some of the material and prevent the dissipation of heat.

16. Since 200° F temperatures can be readily transmitted underground for long distances by convection of steam and combustion gases, the so-called inert porous

barriers (whether manmade or natural rock barriers) may not be effective fire barriers if they are permeable to hot gases. Over a sufficiently long time, the hot gases could breach the barrier to set up spontaneous heating conditions on the "cold" side.

17 Extinguishment actions, such as flushing and trenching, could conceivably alter the underground air and fume circulations in a manner that could cause the development of new regions of spontaneous ignitions. Thus, one might cause the fire to spread to other areas of the mine while extinguishing a known fire zone.

These conclusions are important in considering appropriate fire control options. They are also pertinent to the development of new approaches to fire control and in the application of conventional fire control techniques.

THE CENTRALIA MINE FIRE

It is difficult to generalize about selection of an effective method for controlling mine fires because this choice is based on the specific conditions of any one fire site. For this reason, it is desirable to examine a specific case in depth to see how the adverse conditions in the Anthracite Region have affected propagation of the fire as well as to have a sound basis for recommending future fire control measures.

The Centralia mine fire is a ready example of many of the difficulties encountered in the Anthracite Region. This fire has continued to spread for 21 years despite repeated fire control efforts. The presence of noxious gases in area homes has forced evacuation of several families. Although this fire is now on a larger scale than the typical fire of this region, it does accurately represent the difficulties involved in controlling anthracite mine fires.

BRIEF HISTORY OF MINING IN THE TOWN

Centralia Borough (figs. 7-8) incorporated in February 1866, actually had its beginnings about 1841 when a town known as Bull's Head (later known as Centreville) existed. The first store opened in 1860, and the Lehigh and Mahonoy Railroad entered the town in 1865.

Coal was first mined in the Centralia area in 1842. The Centralia Colliery was developed in 1862, the Continental Colliery was opened in 1863, and the Locust Run Colliery in 1867. The Lehigh Valley Coal Co. operated the Centralia Mine until 1925, after which many miners opened bootleg coal holes or independent mines until mining declined in 1933. In 1935 the Centralia Mine was reopened as the Centralia Mining Co. (also referred to as the Birtley Coal Co.). Ed Whitney, a strip mine contractor for the company, excavated the outcrop of the Buck Mountain Coalbed at this time. In 1945, the Centralia Mine was taken over by John Rich, who sold it to the Rooster Co. in 1955. A short time later the mine was sold to the Coates Coal Co., and in 1962 the Marian Mining Co. became associated with the Coates Co. in a limited operation, which ceased in 1963.

HISTORY OF FIRE CONTROL EFFORTS

In May 1962, a fire was discovered burning in refuse material in a waste disposal area operated by the Borough of Centralia southeast of town in the vicinity of the Odd Fellows Cemetery (fig. 9). The disposal area was an abandoned stripping pit, originally mined in 1935 by Ed Whitney. In 1962, the surface and mineral rights were owned by the Germantown Park Coal Co. The surface was leased to the Jeddo-Highland Coal Co. for stripping, and the mineral rights were given to the Susquehanna Coal Co. for deep mining. Borough workers poured water on the fire and attempted to blanket the affected area with clay. The strip pit was approximately 75 feet wide, and 50 feet deep from the natural surface to the bottom slate of the bed. However, the fire continued to burn and spread to an

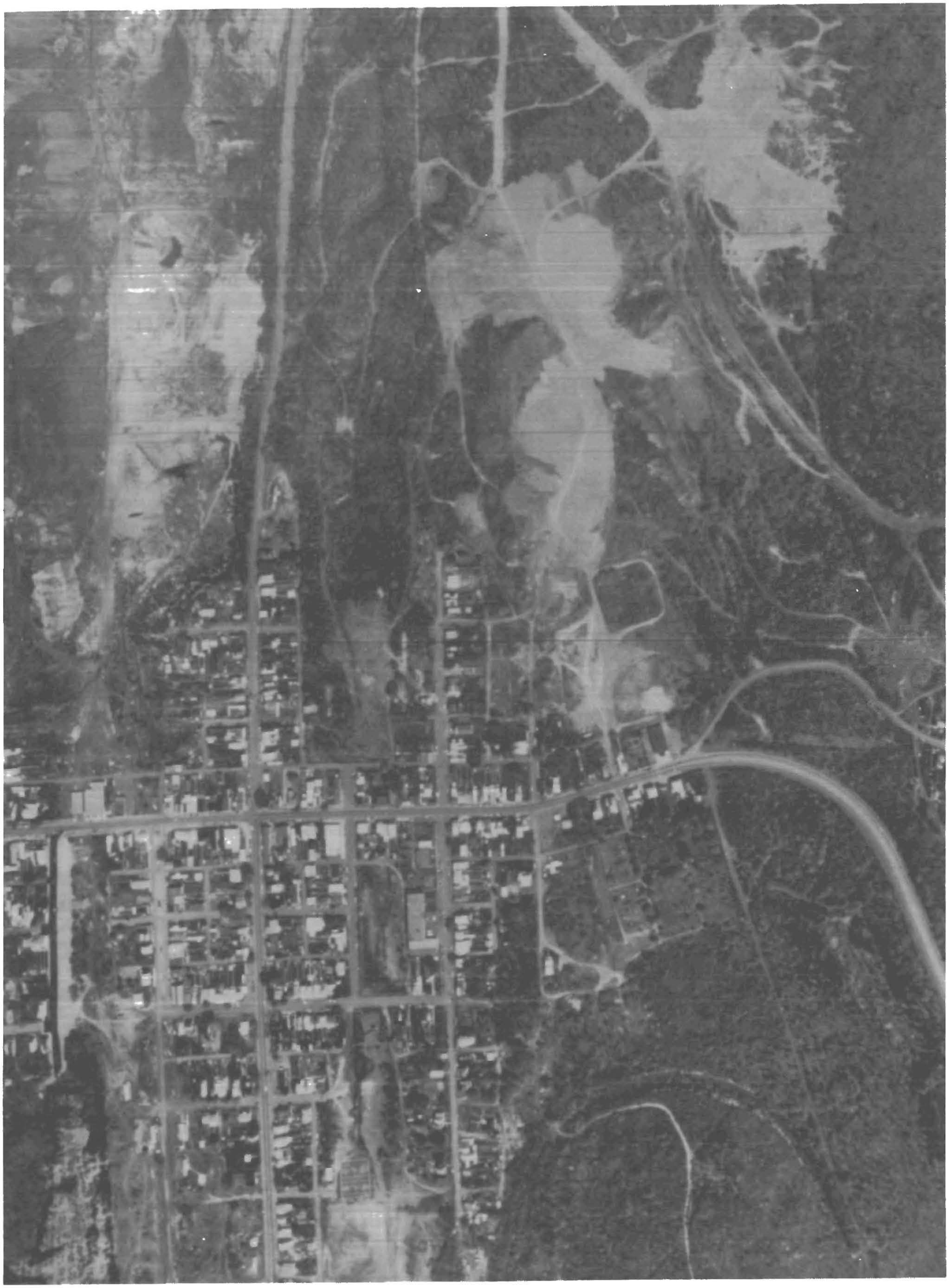


FIGURE 7. - Aerial phc

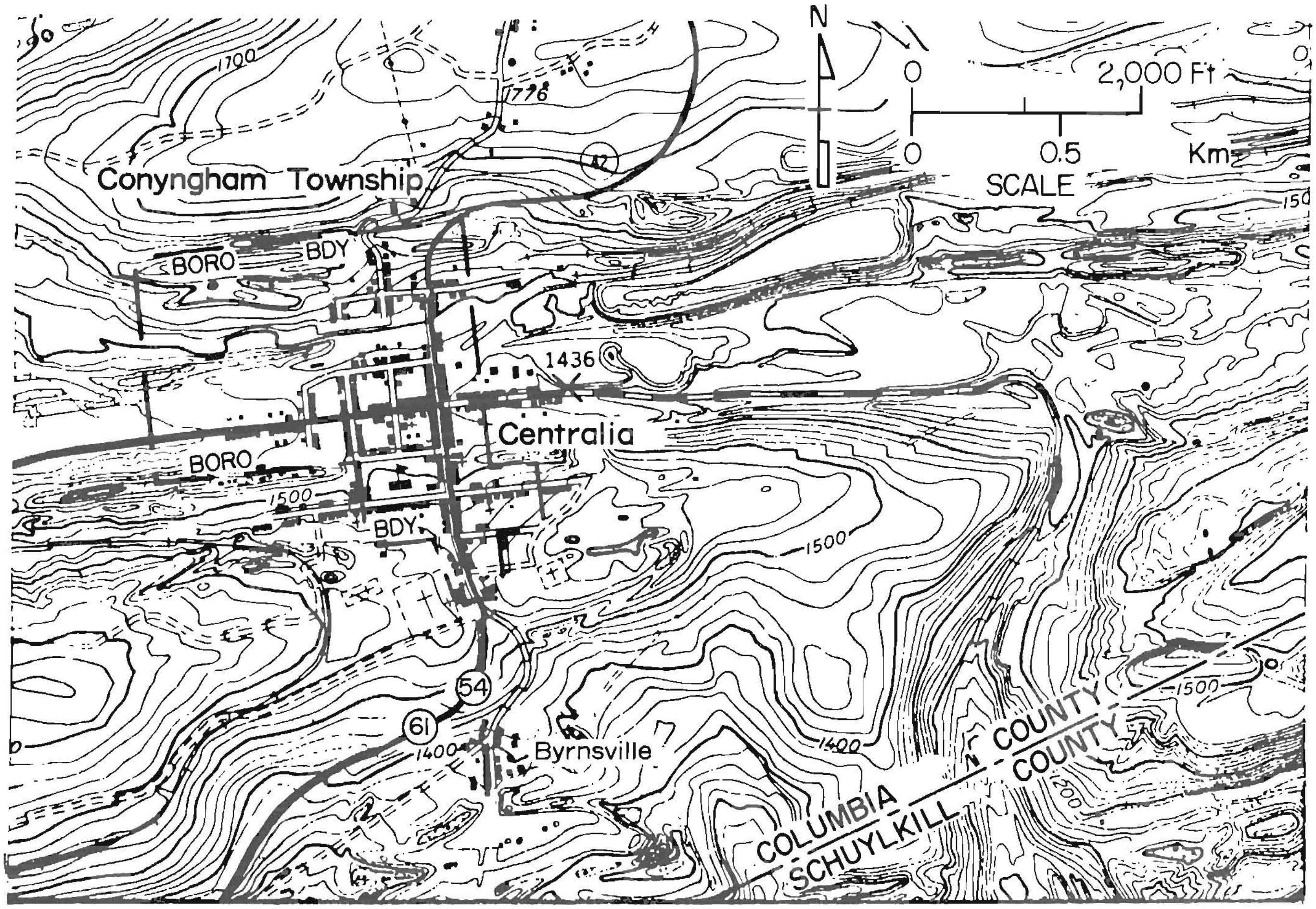
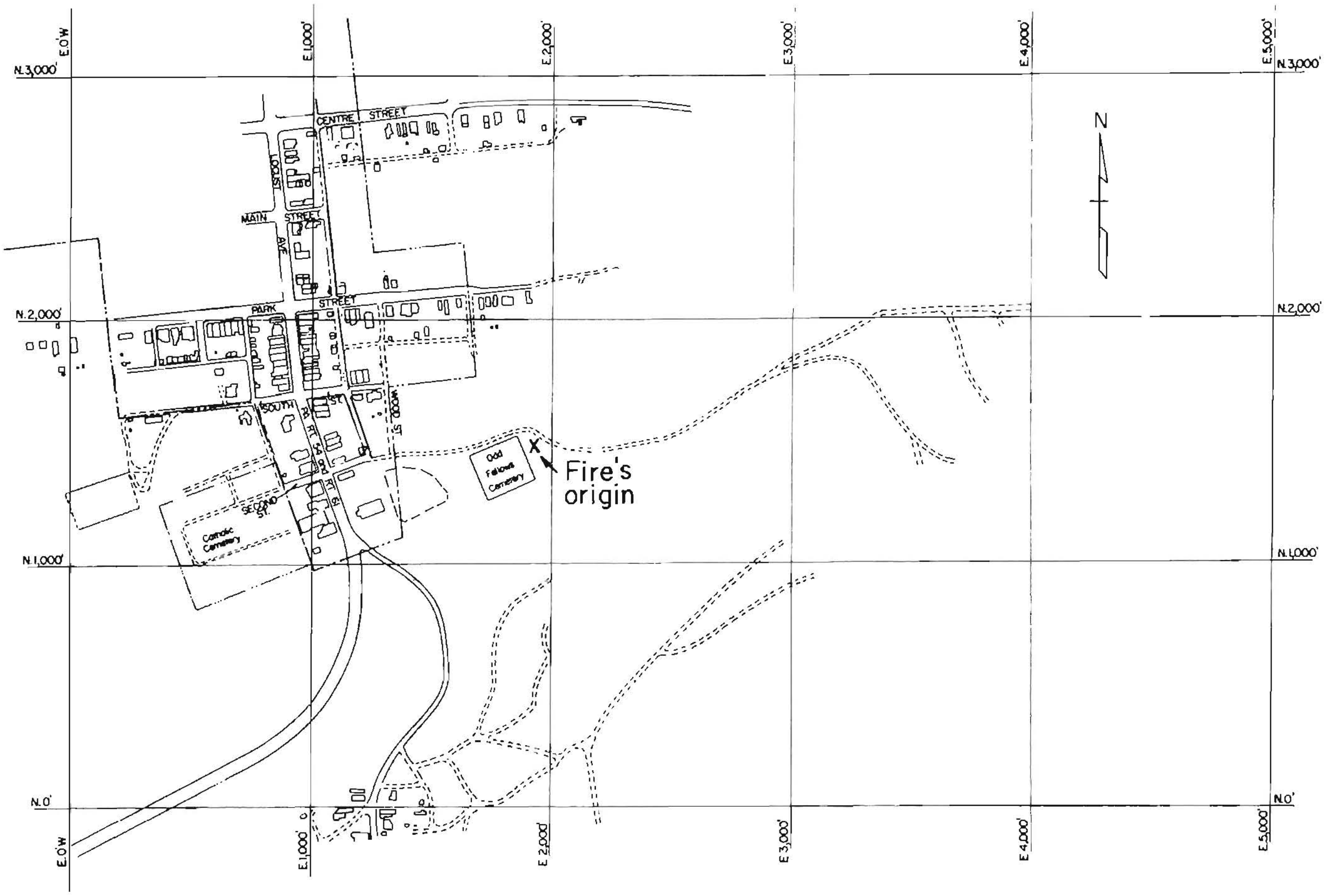


FIGURE 8. - Topographic map of Centralia area, Ashland Quadrangle.

outcrop of the Buck Mountain Coalbed. At this point, controlling the fire was beyond the means of the borough. By July 1962, the fire had progressed through the coalbed almost 200 feet along the strike. The Buck Mountain bed was not exposed, but dense fumes and vapor were emanating along the face of the highwall.

On July 25, 1962, the Deputy Secretary of the Pennsylvania Department of Mines and Mineral Industries reported the mine fire in the stripping outcrop east of Centralia Borough to the Research Director, Division of Anthracite, Bureau of Mines, Schuylkill Haven, PA. On July 26, 1962, Bureau of Mines personnel and engineers from the Pennsylvania Department of Mines and Mineral Industries inspected the site and discussed possible alternatives for combating the rapidly spreading fire. On July 30, 1962, the requirements for obtaining Federal assistance under Public Law 738, at that time the only available Federal program that provided for the control and extinguishment of outcrop and underground fires in coal formations, were discussed with councilman J. Tighe, acting on behalf of the borough. Under Public Law 738, the Bureau of Mines could participate if specific conditions were met: (1) The status of the mine (active or inactive), a practical control plan, and the quantity of reserves had to be determined; (2) a cooperator for 50 pct of the funds was necessary, and the Bureau had to have funds available. It was recognized that the situation was serious and required immediate action.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AVE
PARK STREET
SOUTH ST.
WOOD ST.
PA RT 54
RT 61
SECOND ST.
Catholic Cemetery
Odd Fellows Cemetery
X
Fire's origin

FIGURE 9. - Approximate location of origin of Centralia mine fire.

On August 6, 1962, a meeting of representatives of the Susquehanna Coal Co., Lehigh Valley Coal Co., Commonwealth of Pennsylvania and the U.S. Bureau of Mines was held at the Centralia mine fire site. The consensus was that the fire must be extinguished as soon as possible as it appeared that the fire was spreading rapidly. Fumes from the fire often were carried into the borough.

In addition, the fire had advanced far enough to allow fumes and carbon monoxide to migrate through the abandoned workings of the Centralia Colliery, once owned and operated by the Lehigh Valley Coal Co. When the fumes entered active workings of the Coates Coal Co. and other deep independent mines in the vicinity, these mines could not be permitted to operate. The Commonwealth ordered the closure of 23 mines, putting 140 employees out of work. The fire also posed a threat to surface structures, such as the IOOF (Odd Fellows) Cemetery which adjoined the western end of the pit, and the St. Ignatius church, school, and playground. If left unchecked, it would continue to burn toward other areas of Centralia and might result in the permanent unemployment of local independent miners and loss of private property.

It was decided that the best means of extinguishing the fire was to strip the highwall to the bottom slate of the burning bed until the limits of the fire were reached, excavate the burning material, quench it, and backfill the excavation. The Buck Mountain Coalbed had been first- and second-mined and only a fraction of the original coal remained. It was estimated that the work would require the removal and replacement of 24,000 cu yd of material at an estimated cost of $30,000.

At the meeting, it was stated that approval for Bureau of Mines participation would require about 3 months. Since there was a need for immediate action, it was recommended that the owner and various lessees should pool their resources and start the work as soon as possible. The lessees stated that they lacked funds to participate in the project. The then Deputy Secretary of Mines recommended to the Secretary of the Pennsylvania Department of Mines and Mineral Industries that the Commonwealth undertake this project alone. In order to expedite the work, the Commonwealth assumed the job without financial assistance and solicited bids for the contract work without advertising.

On August 22, 1962, Bridy, Inc., of Atlas, PA, was awarded a contract and began excavating the burning material. A total of 53,580 cu yd of material was excavated before the project was stopped on October 29, 1962, after expending $27,658 (table 3). On October 23, 1962, the Deputy Secretary of Mines had notified the Secretary that the fire had advanced beyond the excavation. It was recommended at that time that excavation be discontinued, and that drilling and flushing be used to stop the flow of air to the fire. Cost of the new project was estimated at $40,000.

On November 19, 1962, K & H Contracting Co. began this second project, which included drilling 80 boreholes and flushing 10,000 cu yd of fine breaker refuse to surround the fire (fig. 10). The fine breaker refuse, obtained free from a slush bank of the Centralia Colliery, was supposed to fill mine voids and minimize the flow of oxygen to the fire. The work continued until March 15, 1963, when funds were depleted ($42,420). No effective control had been achieved. The limited supply of water and the weather were given as constraining factors in accomplishing the work.

In May 1963, Commonwealth personnel reviewed the project work and concluded that after the expenditure of approximately $70,000, no degree of control had been achieved. The surface effects of the fire were visible 700 feet from its origin: fire had advanced 500 feet along the strike of the bed in 11 months. The intensity of the fire was increasing, as indicated by vapors and gases emanating from crop falls and fissures. The material flushed had apparently arrested the spread of fire westward, but the fire appeared to be spreading rapidly in an easterly direction. Three plans were submitted to the Secretary of Mines and Mineral Industries.

Plan A--Drill exploratory boreholes to delineate the fire area, excavate an open-cut trench 1,247 feet long, and backfill with clay; estimated cost, $296,290.

Plan B--Excavate an open-cut trench to partially encircle the fire and follow with intensive flushing; estimated cost, $160,214.

Plan C--Drill exploratory boreholes and flush 19,800 cu yd of material; estimated cost, $82,310.

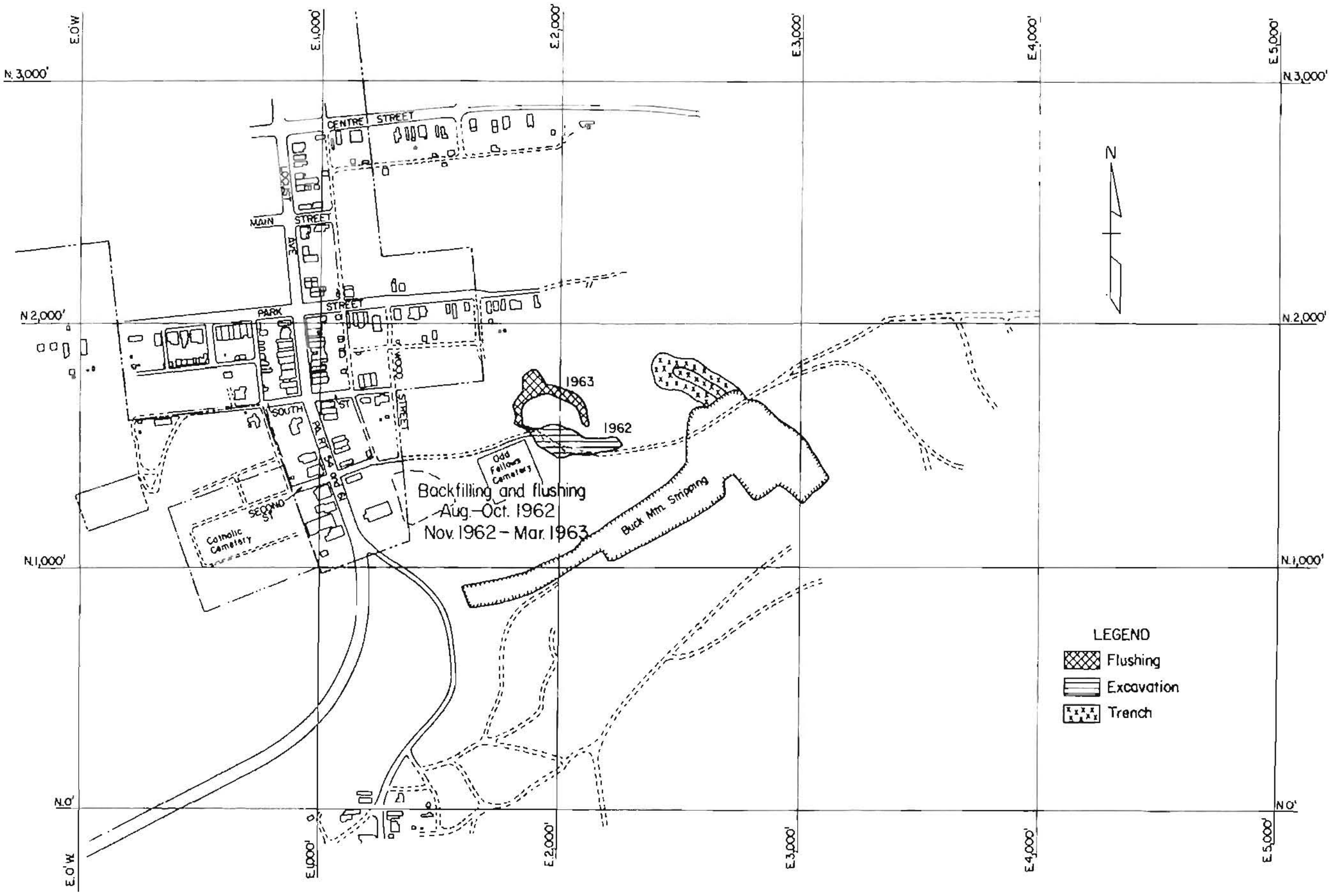
Excavation of the isolation trench (plan B) was considered the most practical way of cutting off and possibly extinguishing the fire. However, since State funds were not available to attempt immediate, large-scale projects to control the rapidly expanding fire, the Centralia mine fire continued to burn.

In July 1963, the Commonwealth made an attempt to control the eastward advance of the fire by trenching. Excavation continued until October 1963, when fire was detected on both sides of the incomplete trench. Total cost of this excavation project was $36,250. By this time, the Commonwealth of Pennsylvania had expended a total of $106,300, but had been unable to control the Centralia mine fire.

TABLE 3. - List of Centralia mine fire projects

Completion year	Brief project description	Cost
1962......	Excavation of burning material near IOOF Cemetery.	$27,658
1963......	Hydraulic flushing of mine voids near IOOF Cemetery.	42,420
1963......	Partial trenching in eastern area........	36,250
1967......	Exploratory boreholes, hydraulic flushing and backfilling near Borough.	326,123
1968......	Reopen some flush boreholes.............	1,530
1970......	Hydraulic and pneumatic flushed underground barrier in western area.	582,693
1973......	Hydraulic flushed underground barrier in eastern area, shallow excavation.	1,858,391
1978......	Partial excavation and flushed barrier reinforcement in western area.	498,138
Total..	-	3,373,203
1980......	Monitoring and assessment of fire control	[1]250,000

[1] Estimated. Costs refer to Interagency Agreement J5101026 (Dec. 31, 1979) between OSM and the Bureau.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LOCUST
MAIN STREET
AVE
PARK STREET
SOUTH ST
PA. RT. 54
LOCUST STREET
SECOND ST
Catholic Cemetery
Odd Fellows Cemetery
1963
1962
Backfilling and flushing
Aug.-Oct. 1962
Nov. 1962 - Mar. 1963
Buck Mtn. Stripping
N
LEGEND
▨ Flushing
☰ Excavation
⁘ Trench

FIGURE 10. - Location of stripping, flushing, and trenching projects by the Commonwealth of Pennsylvania, 1962-63.

On March 9, 1965, Public Law 89-4, the Appalachian Regional Development Act of 1965 was passed by the 89th Congress to "provide public works and economic development programs and the planning and coordination needed to assist in development of the Appalachian Region." Under Section 205 of this act, the U.S. Secretary of the Interior was assigned authority for those projects funded under the act, which were designed to further the economic prosperity of the region by rehabilitating land damaged by previous mining practices, and in particular for the planning and execution of projects for extinguishing underground and outcrop mine fires in the region.

In June 1965, a new project to control the Centralia mine fire was submitted to the Appalachian Regional Commission by the Commonwealth of Pennsylvania in cooperation with the Bureau of Mines. At this time, the fire had consumed an estimated 9 acres, but the actual extent of the fire was unknown. The new project work was planned in two phases.

Phase I would include backfilling and sealing the abandoned stripping pits along the southern edge of the fire to prevent additional oxygen from reaching the fire area, as well as exploratory drilling in the northern, eastern, and western edges to delineate the boundaries of the fire. This was to be followed by the flushing of a temporary noncombustible barrier around the fire area to constrain its expansion while the second phase of the project was being completed. The estimated cost of this work was $300,000.

Phase II was to consist of excavating a permanent isolation trench, approximately 2,500 feet long, on the cold side of the flushed barrier. The trench was to prevent the spread of the fire through the barrier, which might be permeable because of the subsurface caved conditions. The excavation trench would be backfilled with noncombustible material to a level of 20 feet above the coalbed and then backfilled to the surface with waste rock. The depth, estimated at between 100 and 200 feet, precluded trenching without first providing the phase I flushed barrier. The estimated cost of this phase of the work was $2,200,000. At completion of the project, the fire was to be allowed to burn itself out within a confined area, supposedly presenting no further threat to nearby property, local coal reserves, or to the health and safety of local residents.

The Appalachian Regional Commission approved funding for the project on June 8, 1965, at a total project cost of $2,500,000; Federal obligations constituted $1,875,000 or the maximum 75 pct allowed by the act. The contribution contract was signed on July 20, 1966, between the Commonwealth of Pennsylvania, Department of Mines and Mineral Industries; the U.S. Department of the Interior, Bureau of Mines; and the County of Columbia. The Bureau of Mines was assigned responsibility for conducting the work.

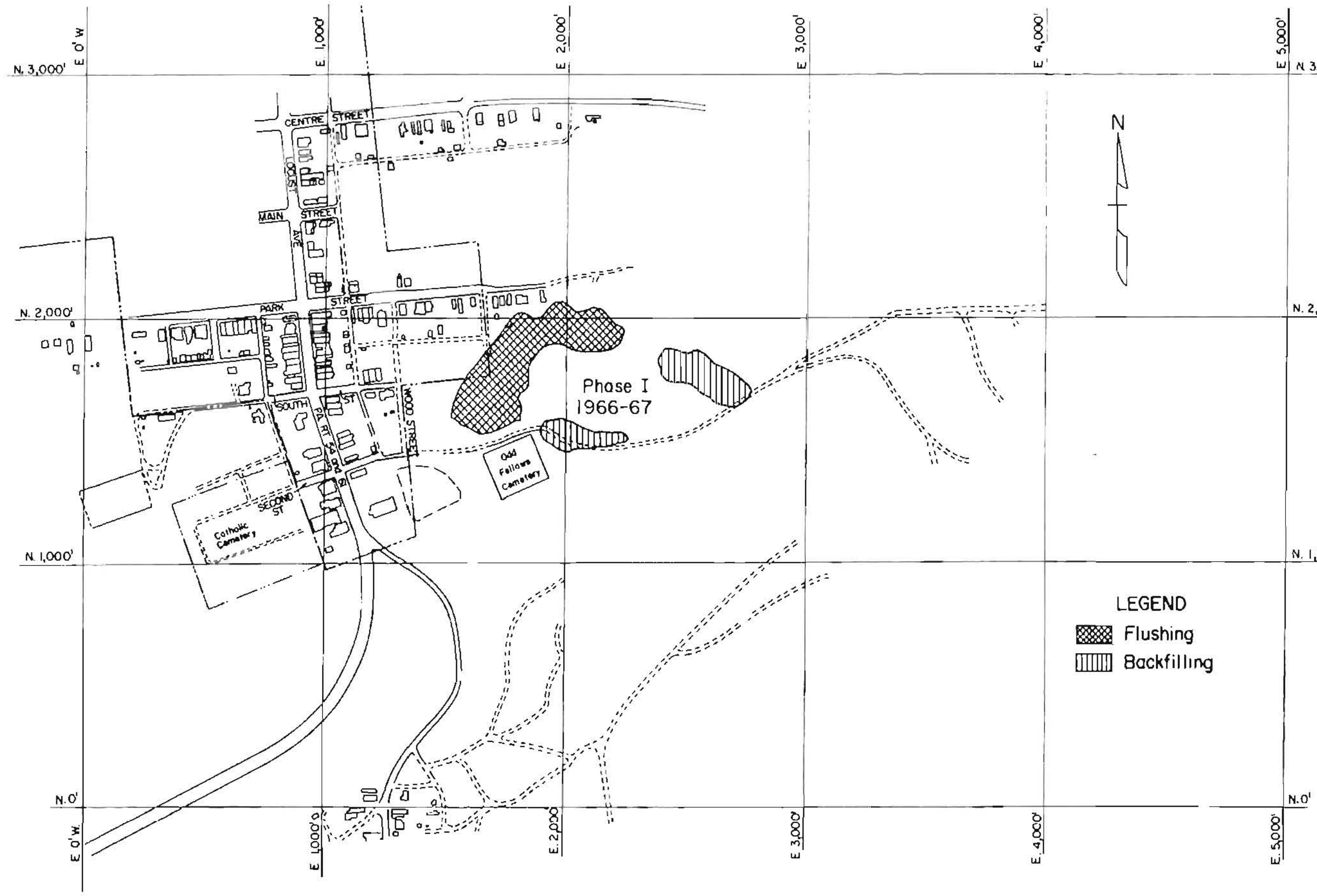
Plans and specifications for the first phase of the project, which included drilling and casing exploratory boreholes to the Skidmore, Seven Foot, and Buck Mountain Coalbeds, flushing of mine voids to arrest spread of the fire in the direction of Centralia Borough, and backfilling certain stripping pits along the outcrop, were advertised for bids on July 21, 1966. The low bid was $281,215, by Empire Contracting Co. of Old Forge, PA. Since this bid, plus the Bureau's 16 pct planning and engineering fee exceeded the estimated cost for phase I work, the contribution contract was amended on September 12, 1966, to increase the phase I cost limit to $360,000 and the total project cost to $2,560,000. The construction contract was awarded to Empire. Work began on November 7, 1966.

The steep dip of the coalbeds and the caving caused by extensive mining, along with the necessity to prevent propagation of the fire to other coalbeds, made this project difficult. In the first phase of the work, the open pit adjacent to the Odd Fellows Cemetery and the open trench at the east end of the mine fire area were backfilled with noncombustible material available on site. A small part of both the open pit and trench were left open to serve as vents. Mine workings under the northwest corner of the project area were flushed shut with sand. A total of 116 exploratory boreholes and 97 flushing boreholes were drilled and 81,000 cu yd of sand flushed into the mine voids (fig. 11). Phase I of the project was completed on November 30, 1967. The total cost was $326,123 (18).

During exploratory drilling, it was determined that the fire had progressed further north and east than originally anticipated, but was still within a controllable area. During flushing operations, unusually large voids had been encountered which accepted more material than originally estimated.

On January 25, 1968, Tully Drilling Co. was awarded a contract of $1,530 to reopen boreholes that had been blocked or flushed with 1-inch noncombustible material, and originally cased with 6-inch steel casing pipe. Drilling was started on February 2, 1968, and completed on February 12, 1968. Sixteen holes were reopened, 10 of which were flushed holes. In the flush holes, the loss of drill air (120 psi) in 6 of the 10 holes indicated that flushing material was present, but did not form an effective barrier. In 4 of the 10 holes, the material did provide an airtight seal.

In order to implement phase II as originally envisioned, an isolation trench more than 300 feet deep would have to be excavated, through very hard rock. This approach would be costly, estimated at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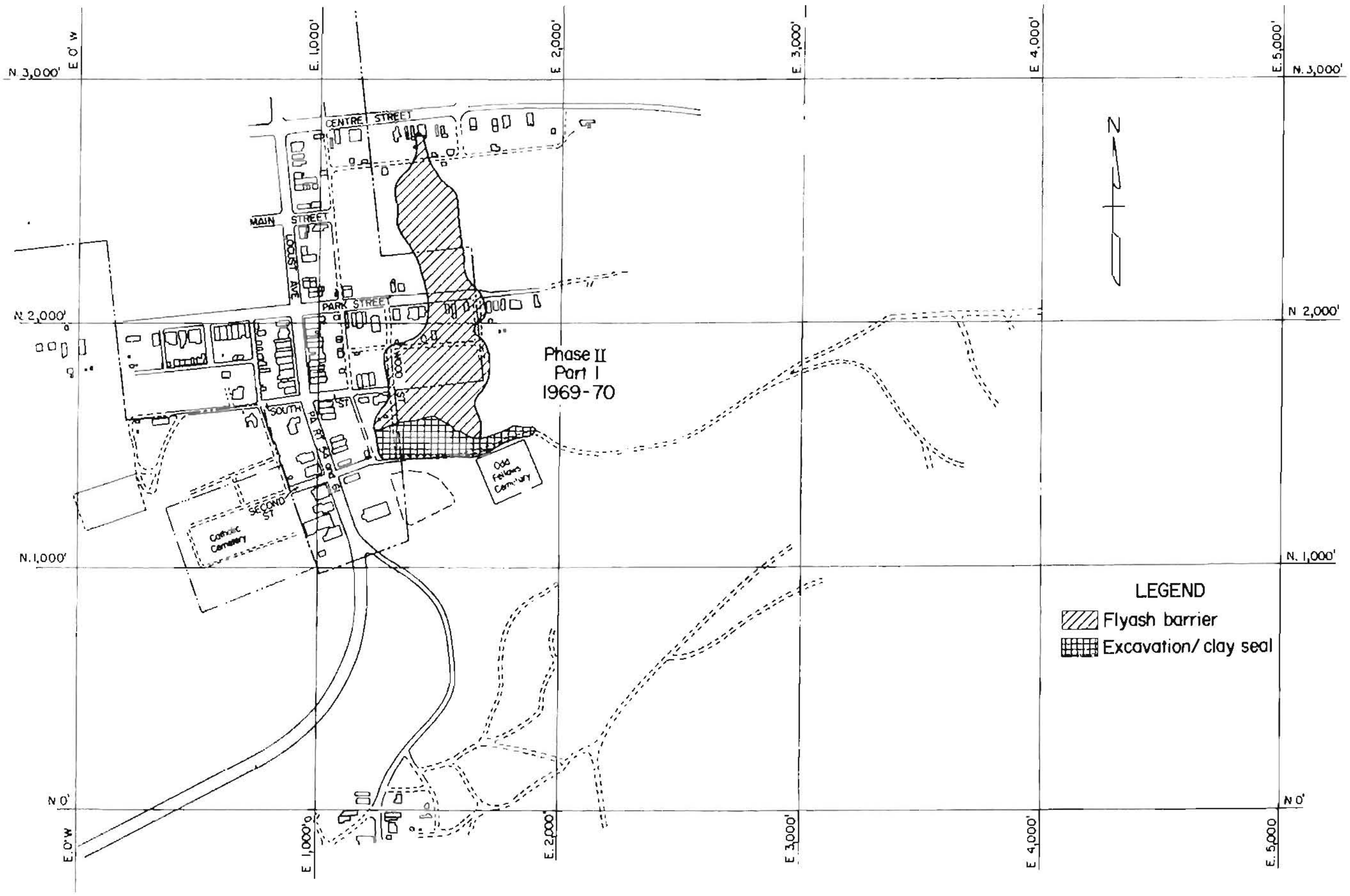
WOOD STREET
SECOND ST
Catholic Cemetery
Odd Fellows Cemetery
Phase I
1966-67
N
LEGEND
Flushing
Backfilling

FIGURE 11. - Location of backfilling and flushed barrier (phase I), Federal-State project, 1967.

approximately $4.5 million, and time consuming. Since time and available project funds were limited, it was decided to construct underground barriers to prevent the spread of the mine fire to the east and west, while the mine water pool would limit the northward progress of the fire. The first part of the revised second phase would involve construction of an underground barrier west of the fire area, extending from the outcrop and curving around to the mine water pool. Boreholes would be drilled as necessary into the underground mine voids in the Buck Mountain Coalbed and pneumatically filled with fly ash. Fly ash, an ultrafine noncombustible smokestack residue from coal-burning electric powerplants, would be supplied to Columbia County free of charge. This was to be the first application of fly ash for controlling a mine fire in the Anthracite Region, although this technique had been used successfully in the bituminous area. The installation of fly ash barriers was considered a demonstration. They had been used previously to control an underground fire, in which the coalbed was extensively caved and the pitch of the bed ranged from 0° to 20°. A later part of the second phase would be to construct a similar barrier to the east of the fire area.

Plans and specifications for the western barrier, which was to run parallel to Wood Street, were advertised for bids on February 5, 1969. The low bid, by the Stearns Service Co., Inc., of Wilkes-Barre, PA, was $518,840, including drilling and casing boreholes, injecting screened noncombustible material to form a buttress, and pneumatically injecting flyash into mine voids to form a barrier to control the westward spread of the fire. On April 7, 1969, the contract was awarded, and work began on May 5, 1969.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SOUTH ST
SECOND ST
Catholic Cemetery
Odd Fellows Cemetery
Phase II
Part I
1969-70
N
LEGEND
Flyash barrier
Excavation/ clay seal

FIGURE 12. Location of excavation and western noncombustible barrier (phase II, part 1), Federal-State project, 1969-70.

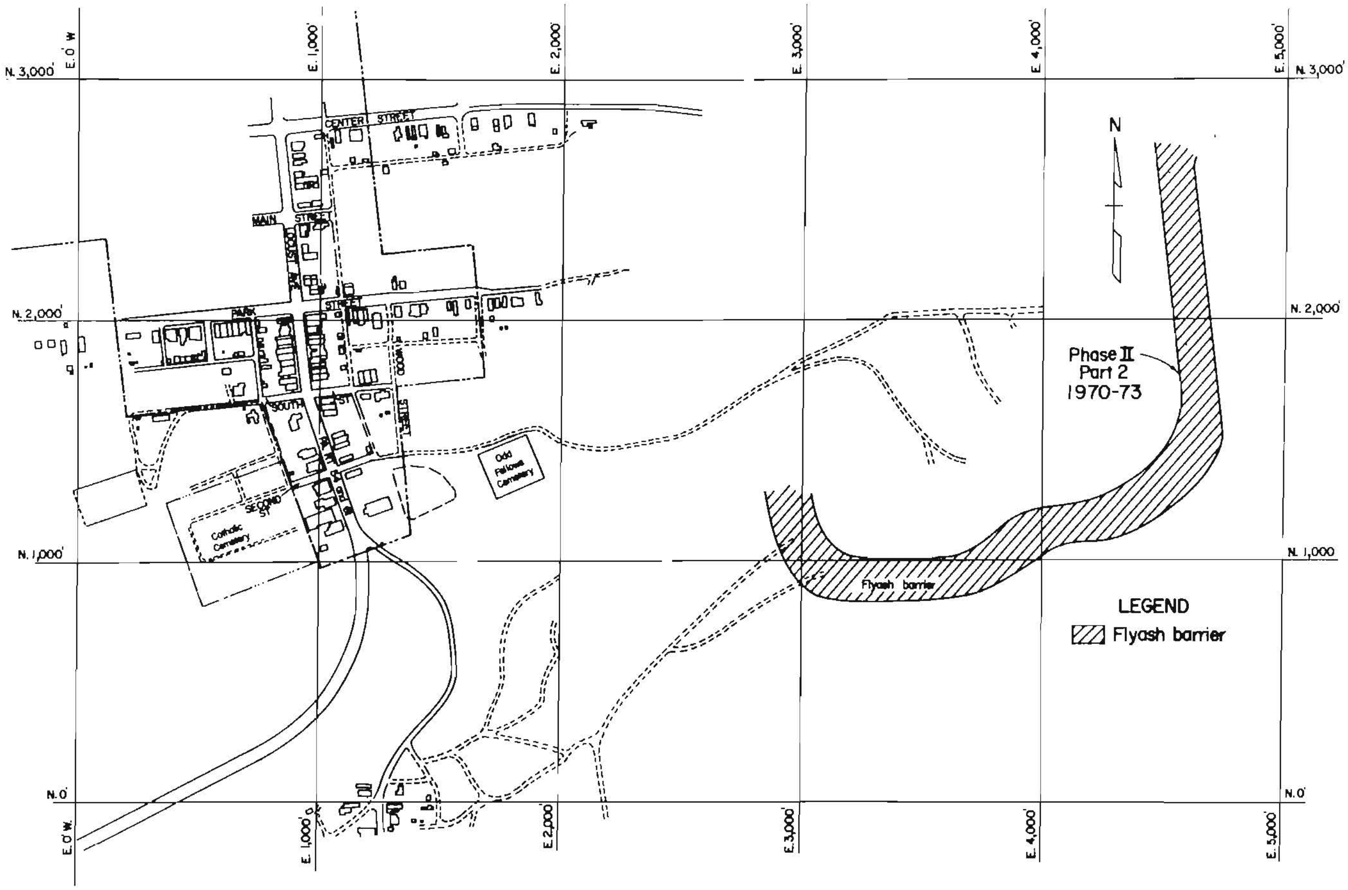
On May 22, 1969, three families at Wood and South Streets had to vacate their homes when oxygen deficiency and a trace of carbon monoxide were detected in the cellar of one of the homes by State mine inspectors. Traces of carbon monoxide were also detected on June 11. On May 20, 1969, temperatures of 760° F and 900° F were recorded in two monitoring boreholes southeast of the homes, near the mined coalbed outcrop. Apparently, the fire was advancing westward, in the vicinity of Wood Street and the Odd Fellows Cemetery. This advance along the southern fringe of the project area threatened to bypass the barrier before it could be constructed. To prevent this, injection was started from the pit northward along the east side of the borough on May 26, ahead of schedule (fig. 12). Also, the fire in that location was excavated, and the burning material was removed, quenched, and placed in nearby shallow stripped areas. A clay seal was placed in the excavation area along the face of the exposed bed to cut off oxygen to the fire. A total of 60,000 cu yd of material was excavated, 18,883 cu yd of clay emplaced, and 12,333 tons of coal removed (19).

The injection work continued until August 8, 1970. Three hundred sixty-two boreholes were drilled a total of 69,332 linear feet; individual depths were over 400 feet. Two hundred and eighty-one holes, including exploratory holes, fly ash holes, and flushing holes, were drilled along and near the western perimeter of the mine-fire area in the vicinity of the fly ash and clay barrier. In three fly ash holes drilled in the vicinity of the dump pit from which the fire originated, temperatures of 550° F, and 402° F were recorded. In exploratory holes, located 300 feet east of the fly ash-clay barrier, in the fire area, a temperature of 612° F was recorded. In the remaining 277 holes, temperatures ranged from 56° F to 300° F.

The injection of 39,272 tons of fly ash was intended to form an underground barrier 10 feet deep, approximately 150 feet wide, and 1,100 feet long. Sixty-eight percent of the fly ash (26,786 tons was pneumatically injected to fill mine voids in the Buck Mountain bed. Eighteen percent (7,026 tons) was injected into the Seven Foot bed, and the remaining 14 pct (5,460 tons) into the Skidmore bed. Screened coarse noncombustible material was hydraulically injected into the mine workings to form a buttress between the fly ash and the underground water pool. About 3,000 cu yd was injected into the Buck Mountain bed, 1,998 cu yd into the Seven Foot bed, and 74 cu yd into the Skidmore bed; 1,000 cu yd was flushed into the Buck Mountain Tunnel and 5,492 cu yd was flushed into the Buck Mountain Slope. The total project cost for the western barrier was $582,693.

Eighty-one exploratory holes were drilled along the eastern and southeastern perimeter of the mine-fire area. Temperatures between 58° F and 300° F were recorded in 71 holes. In eight holes the temperature of the Buck Mountain Coalbed ranged between 300° F and 600° F, and in two holes temperatures between 700° F and 800° F were recorded. During the week of August 10-14, 1970, a temperature survey of the exploratory holes showed 62 with temperatures between 600° F and 900° F. The holes with the increasing temperatures were in the southeastern area where the underground fire was apparently crossing the anticline.

On August 19, 1970, a contract was awarded to Stearns Service Co., Inc., the low bidder at $1,352,125, for construction of the eastern barrier. Work started on August 25, 1970. Installation of the barrier required the hydraulic injection of 36,220 cu yd of noncombustible, sandy clay and pneumatic injection of 83,084 tons of fly ash. The noncombustible barrier was to be about 2,600 feet long and 160 to 300 feet wide (fig. 13). A total of 1,049 boreholes were drilled, averaging 204 feet in depth. Of these 1,017 were fly ash boreholes and 32 were flushing boreholes.


N. 3,000'
E. 0' W
E. 1,000'
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N. 1,000'
N. 0'
CENTER STREET
MAIN STREET
PARK STREET
SOUTH ST
SECOND ST
Odd Fellows Cemetery
Catholic Cemetery
N
Phase II Part 2 1970-73
Flyash barrier
LEGEND
▨ Flyash barrier

FIGURE 13. - Location of eastern noncombustible barrier (phase II, part 2), Federal-State project, 1970-73.

While this work was in progress, there was a high-temperature breakthrough at a completed section of the fire barrier. This required drilling additional boreholes and injection of fly ash in excess of the original estimates. The additional expense required increased funding of $207,282, which was approved by the Appalachian Regional Commission on September 22, 1972, and an amendment of the contribution contract, executed on October 22, 1972. Work on the project was suspended from August 1972 until February 1973 while awaiting approval of the additional funding. Work on the eastern barrier was completed on December 14, 1973. The cost of this phase of the project was $1,858,391 (20).

During the 7-year joint Federal-State project, approximately 1,635 boreholes had been drilled, 122,556 tons of fly ash injected, and 117,220 cu yd of sand flushed. Approximately 60,000 cu yd of material had been excavated, and almost 19,000 cu yd of clay seals installed, with appropriate backfilling, grading and revegetation. The total cost of the project was $2,768,208, of which 75 pct or $2,076,156 was contributed by the Federal Government.

During the project, 13 monitoring boreholes had been installed along the cold site of the permanent barrier. Temperature changes in these boreholes would indicate areas of weakness in the barrier. The boreholes were monitored weekly, and, in the latter part of 1975 and the early part of 1976, elevated temperatures were detected in 6 of the 13 holes. Two of the boreholes also showed traces of carbon monoxide. By August 3, 1976, the maximum temperatures were 166° F, an increase of 97° over the temperature recorded in 1967. By June 1977, the temperature had increased to 170° F and carbon monoxide was detected in another borehole. This detection of gases did not necessarily mean that the barrier had been breached. The original barrier was either incomplete at this point, or had settled enough to allow gas to seep over the seal and through the rock fractures and fissures. A proposal to reinforce the barrier was formulated and submitted to the Appalachian Regional Commission on March 28, 1977. This project would involve two phases. The first phase would involve drilling additional monitoring boreholes to determine the extent of the current problem. The second phase would consist of flushing noncombustible material to reinforce the existing barrier, or to create new barriers as needed. In addition, two major surface vents to the fire would be sealed, and burning strip overburden would be spread and quenched. The project was approved by the Commission on April 12, 1977, at a total cost of $385,000.

The plans and specifications for this project were approved by the Secretary of the Interior on August 9, 1977. A contribution contract was executed by the Commonwealth of Pennsylvania, Columbia County, and the United States of America on August 18, 1977, and on August 19, the project was advertised for bids. The lowest bid, from the L. R. Costanzo Co., Inc., of Scranton, PA, was $429,550, which, with the associated plannning and engineering charges, was more than the approved project amount. Additional funding of $113,279 was approved by the Appalachian Regional Commission on December 5, 1977, and the contribution contract was amended to the increased amount on December 23. The contract was awarded on January 30, 1978. Work began on February 1, 1978, and was completed on November 21, 1978. It included the injection of 7,180 tons of fly ash, the excavation and removal of 150,600 cu yd of burning material, the addition of 40,375 cu yd of material as backfill, and the drilling of 58 boreholes. The total cost was $498,138.

Because of the increasing concern of local residents, a meeting was held with Federal, State, and local representatives and residents to discuss the possibility of constructing a cutoff trench to further isolate the fire from the Borough of Centralia. As proposed, the isolation trench would have been approximately 415 feet long, beginning where the Buck Mountain bed had been excavated and proceeding to the center of Poplar Street. The maximum width of the trench at the surface would have been 155 feet and its maximum depth 140 feet. The Appalachian Regional Commission approved the request for an additional $464,000 to begin the trench on August 22, 1978. An amendment to the Contribution Contract was prepared and sent to Columbia County for execution. However, although the trench was designed to minimmize surface disturbance, it would have required the destruction of several private homes. Since the Bureau lacked the authority and funds to purchase these homes, agreement was never reached with Columbia County. After reviewing all the factors involved, the proposal for the cutoff trench was dropped.

To allay the anxieties of the residents living closest to the fire area, the Bureau of Mines installed carbon monoxide detectors in 10 homes, and Pennsylvania inspectors began making weekly tests for gas seepage.

Under the Surface Mining Control and Reclamation Act of 1977, the Office of Surface Mining (OSM) was formed. As one of its functions, OSM administers a reclamation fund for reclaiming coal-mined lands abandoned prior to passage of the bill. OSM has the authority to perform emergency reclamation work on eligible lands where public health and safety is endangered; however, subsequent to the completion of this study in July 1982, the Commonwealth of Pennsylvania received primacy and now has an approved Abandoned Mine Land Program.

On December 31, 1979, the Bureau of Mines and the Office of Surface Mining entered into an interagency agreement whereby the OSM provided the Bureau of Mines with funds to gather data on the current status of the mine fire and evaluate the possible alternatives for dealing with the fire. The initial task was to drill 36 boreholes along the western perimeter of the fire to determine the boundary of the fire zone. These holes were then used to gather data on underground temperatures, which also were collected in other boreholes previously drilled through the fire area. These temperatures, along with temperature data collected during prior projects, served as the basis for thermal mapping to establish areas of elevated temperatures. This was accomplished both by simply plotting the data on surface and mine maps to show points of elevated temperature, and by a contracted computer analysis of the data to generate isothermal contour maps of the fire area. In addition to these temperature maps, infrared mapping of surface temperatures was done by a contractor using aerial mapping techniques to produce a digital computer printout showing relative surface temperatures as contours. Once the fire area had been defined, the available options for controlling the fire were applied to the situation and assessed for effectiveness, feasibility, and cost. The results of this assessment were submitted in a report to OSM in August 1980. In addition, the Bureau installed 5 additional carbon monoxide detectors in area homes, bringing the total monitored to 15. The Centralia mine fire has not been extinguished and is not controlled. The measures used up to 1980 in attempts to control the fire (fig. 14) have not been effective, and, in some cases, may have influenced the propagation of the fire. The geological and physical conditions, the extent of the fire, and the

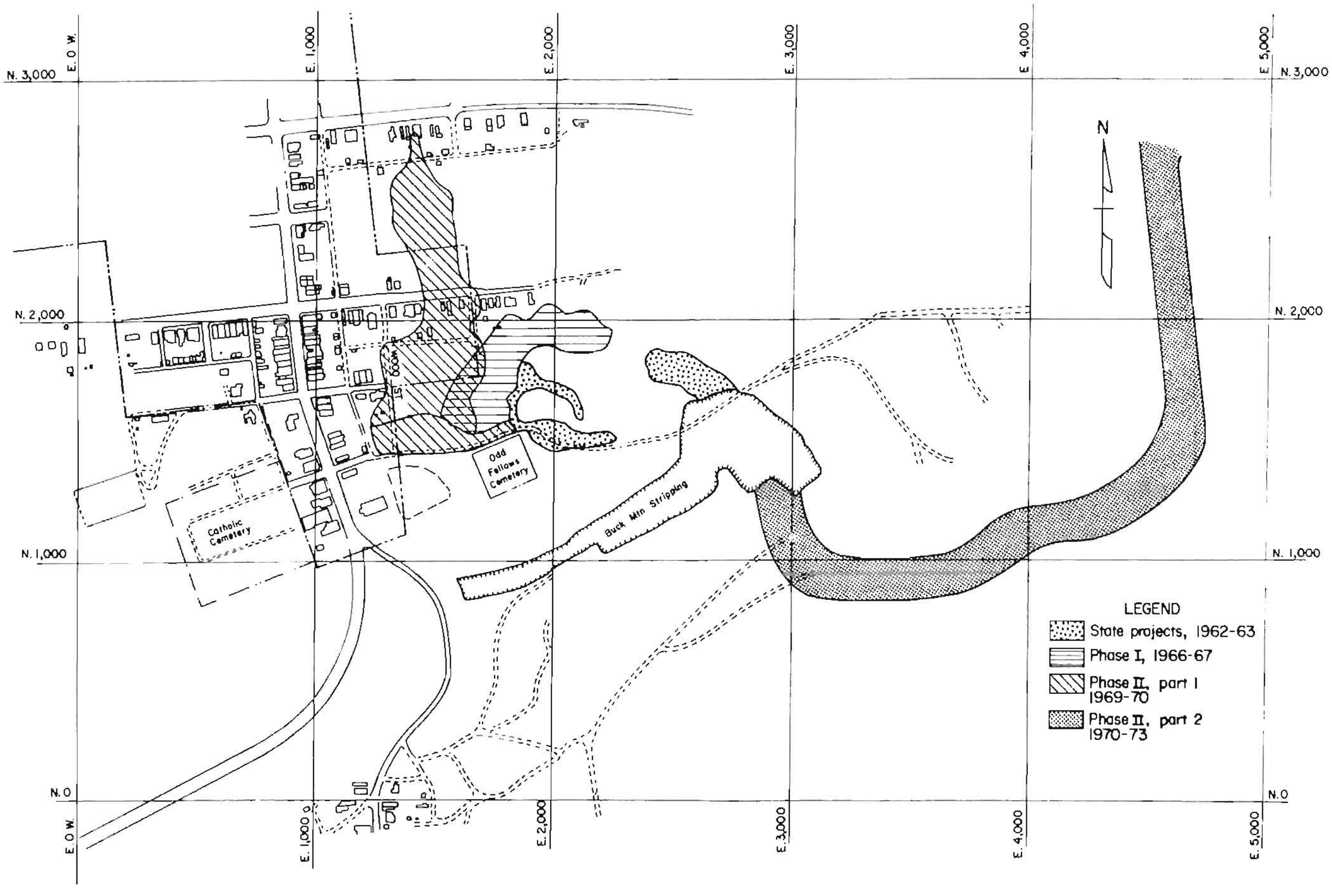

FIGURE 14. - Composite of previous attempts to control Centralia mine fire.

probability of success must be considered in selecting the method(s) to extinguish or control the fire. Additional information and funding are necessary to accomplish the permanent control or extinguishment of the Centralia mine fire.[8]

FACTORS AFFECTING PROPAGATION

The geological and mining conditions in the Western Middle Anthracite Field, including the steep dip of the coalbeds, the fragmented and inhomogeneous gob area, subsidence fractures extending to the surface, and the presence of underground drainage tunnels, have contributed to the difficulty in controlling the Centralia mine fire. The fire started in the Buck Mountain Coalbed, and currently is believed to be confined to this coalbed. The outcrop of the Buck Mountain Coalbed strikes approximately north 77° east and plunges slightly to the east. From the outcrop the coalbed dips approximately 40° along the north limb toward the Centralia syncline, which roughly parallels the anticline 1,700 to 1,800 feet to the north. In the area of the fire, the Buck Mountain Coalbed is overlain by a competent sandstone and siltstone.

One of the complicating factors in bringing the fire under control is the extensive previous mining in the area. The Buck Mountain Coalbed has been surface mined across the nose of the anticline and along the outcrop of the south limb, and it has been extensively deep mined along both dips of the anticline (fig. 15). The north dip has been

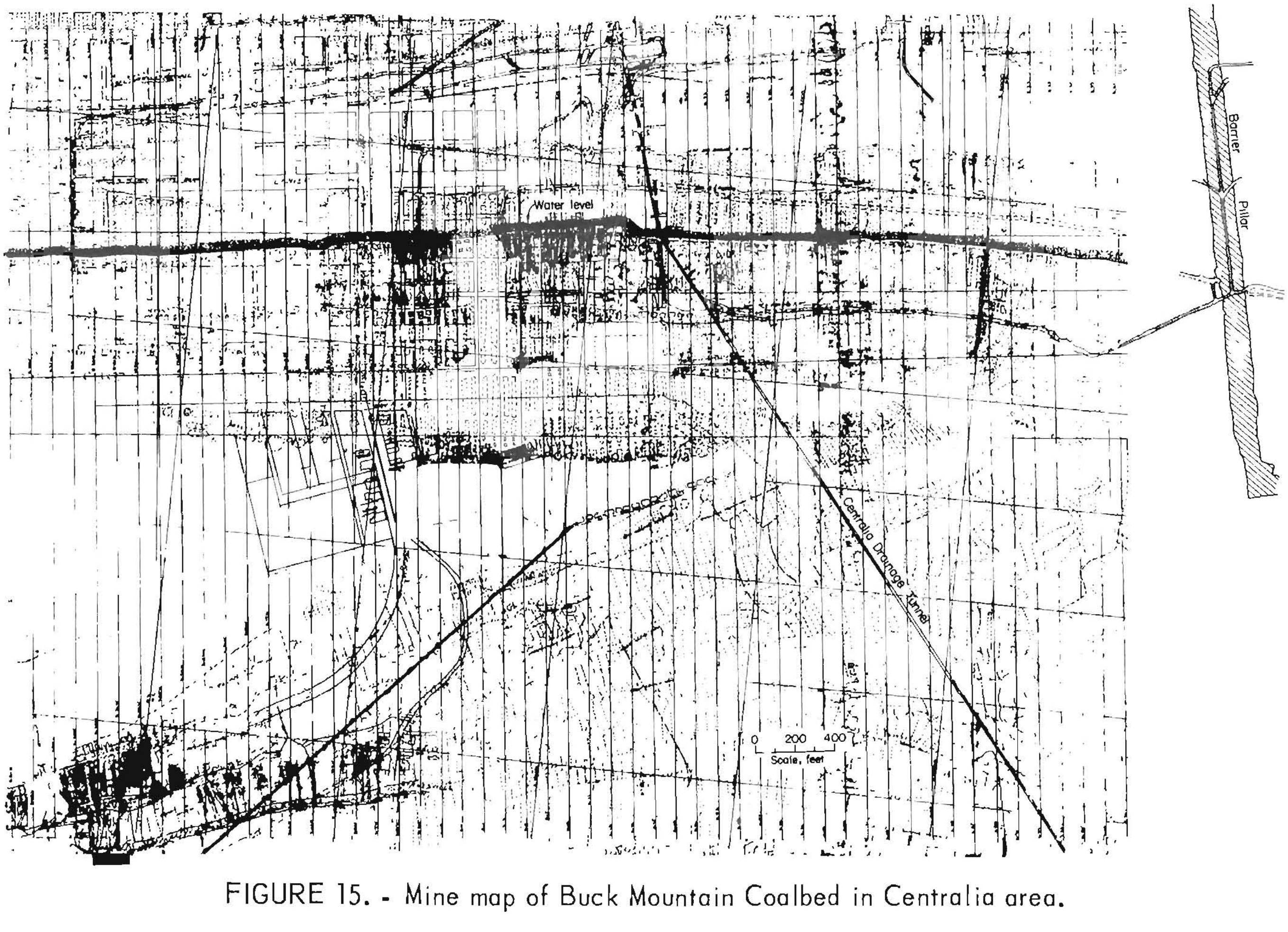

FIGURE 15. - Mine map of Buck Mountain Coalbed in Centralia area.

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[8] OSM and the Pennsylvania Department of Environmental Resources have continued to gather information on this fire since the last Bureau study in 1980. Information from these continued investigations is not included in this report.

third-mined (pillars removed) on the second, third, and fourth levels. The extent of the third-mining on the south dip is uncertain. A barrier pillar between mined-out areas of the Centralia Mine and the Gerrard Estate Collieries has been breached by drainage tunnels (15 feet above the water table) at an elevation of approximately 1,015 feet. The Skidmore and Mammoth Coalbeds have been surface mined on the north dip and also deep mined. The Seven Foot Coalbed has also been mined in the area.

Another important complicating factor caused by previous mining in the area is the Centralia Drainage Tunnel, which was constructed to remove water from the coalbeds to facilitate mining. It intersects the Buck Mountain Coalbed at an elevation of 1,000 feet and discharges into Big Mine Run and Mahanoy Creek at an elevation of 987 feet. Other drainage tunnels and haulageways also intersect the Buck Mountain Coalbed in the area. These tunnels probably affect the fire by acting as sources of ventilation. Drainage tunnels intersecting the coalbed keep the area of the fire dry and bring large quantities of fresh air into the fire zone. Normally, the amount of fresh air available to the fire is dependent on the number of openings to the surface and on changes in barometric pressure. The drainage tunnels may allow the formation of underground convection cells, in which large volumes of air can be drawn into the fire zone at one point and combustion gases exhausted to the surface at another point. The formation of convection cells can therefore increase the rate of combustion and distribution of combustion gases. Drainage tunnels also are a problem when considering extinguishing the fire by flooding.

Another influence in the area is the location of natural barriers to the spread of the fire (fig. 16). The Buck Mountain Coalbed dips north to the water table at 1,000 feet of elevation. The water table prevents the northward propagation of the fire to areas under the major portion of Centralia Borough. The Locust Gap Fault, approximately 4,500 feet south of the Locust Mountain anticline with a vertical displacement of approximately 200 feet, prevents the spread of the fire to the Mahanoy basin. Water in the Germantown Colliery at an elevation of 975 feet prevents the spread of the fire southward toward Ashland. Since the Buck Mountain Coalbed has been eroded along the center of the Locust Mountain anticline, the outcrop limits the propagation of the fire in this area. If the fire were allowed to continue indefinitely, these natural barriers would limit the fire to a surface area of 1,500 acres involving 24 million tons of coal. It would lead to the destruction or creation of hazardous living conditions in 320 homes, businesses, and churches and affect a number of roadways, underground gas pipelines, and surface utilities. There is no natural barrier to prevent propagation of the fire southwest toward Byrnsville.

In addition, temperature data collected from boreholes drilled into the Seven Foot, Skidmore, and Buck Mountain Coalbeds support the theory that the propagation of the Centralia mine fire has been affected by the migration of hot combustion gases. The underground temperatures indicate that fire areas are indeed separated by cooler zones (fig. 17). This would not be expected if propagation were exclusively by flame spread.

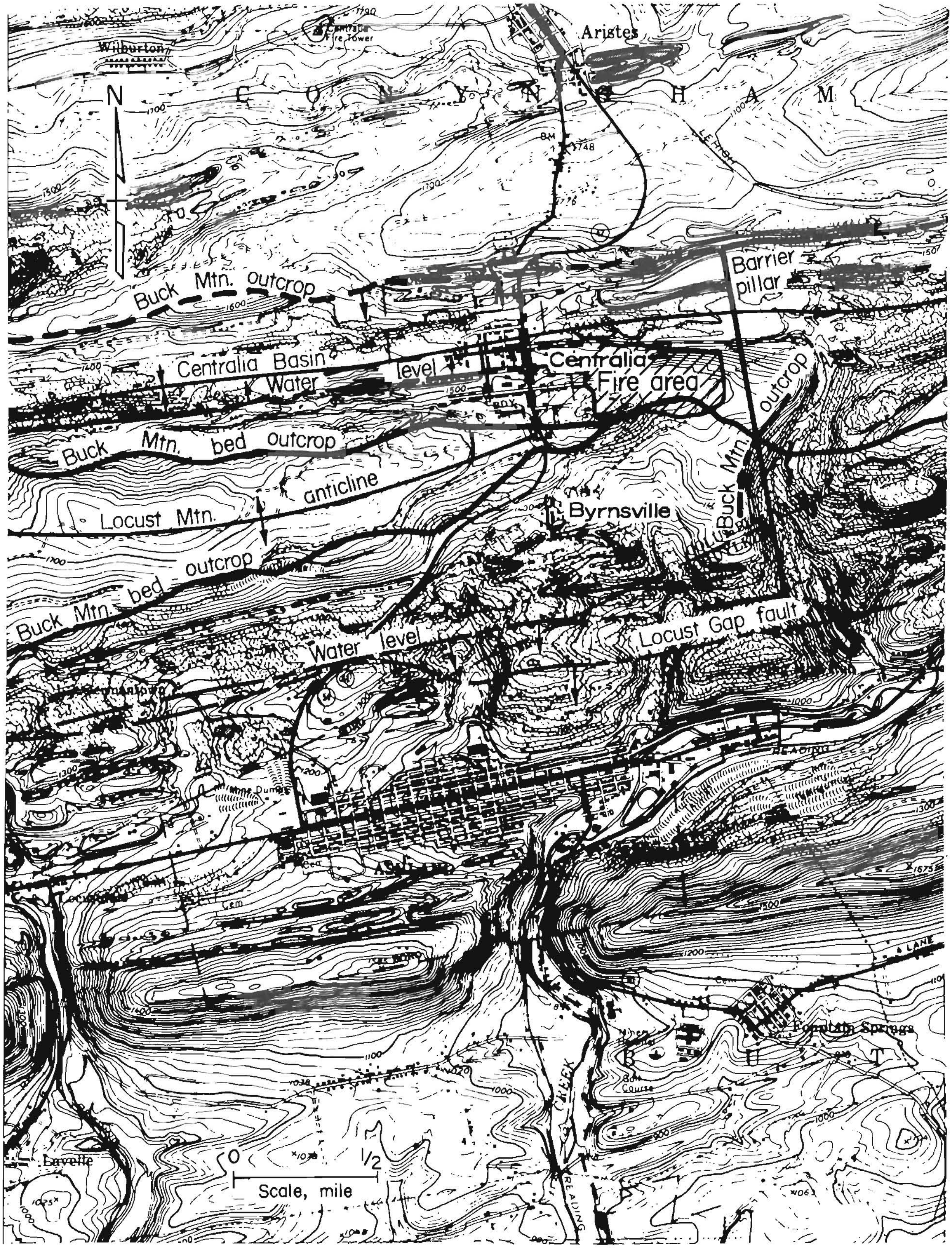
Wilburton
Centralia Fire Tower
Aristes
N
C O N Y N G H A M
Buck Mtn. outcrop
Barrier pillar
Centralia Basin
Water level
Centralia
Fire area
Buck Mtn. bed outcrop
Locust Mtn. anticline
Byrnsville
Buck Mtn. outcrop
Buck Mtn. bed outcrop
Water level
Locust Gap fault
Mine Dump
Fountain Springs
Lavelle
0
1/2
Scale, mile
Creek
Reading

FIGURE 16. - Location of the natural barriers to propagation of Centralia mine fire.

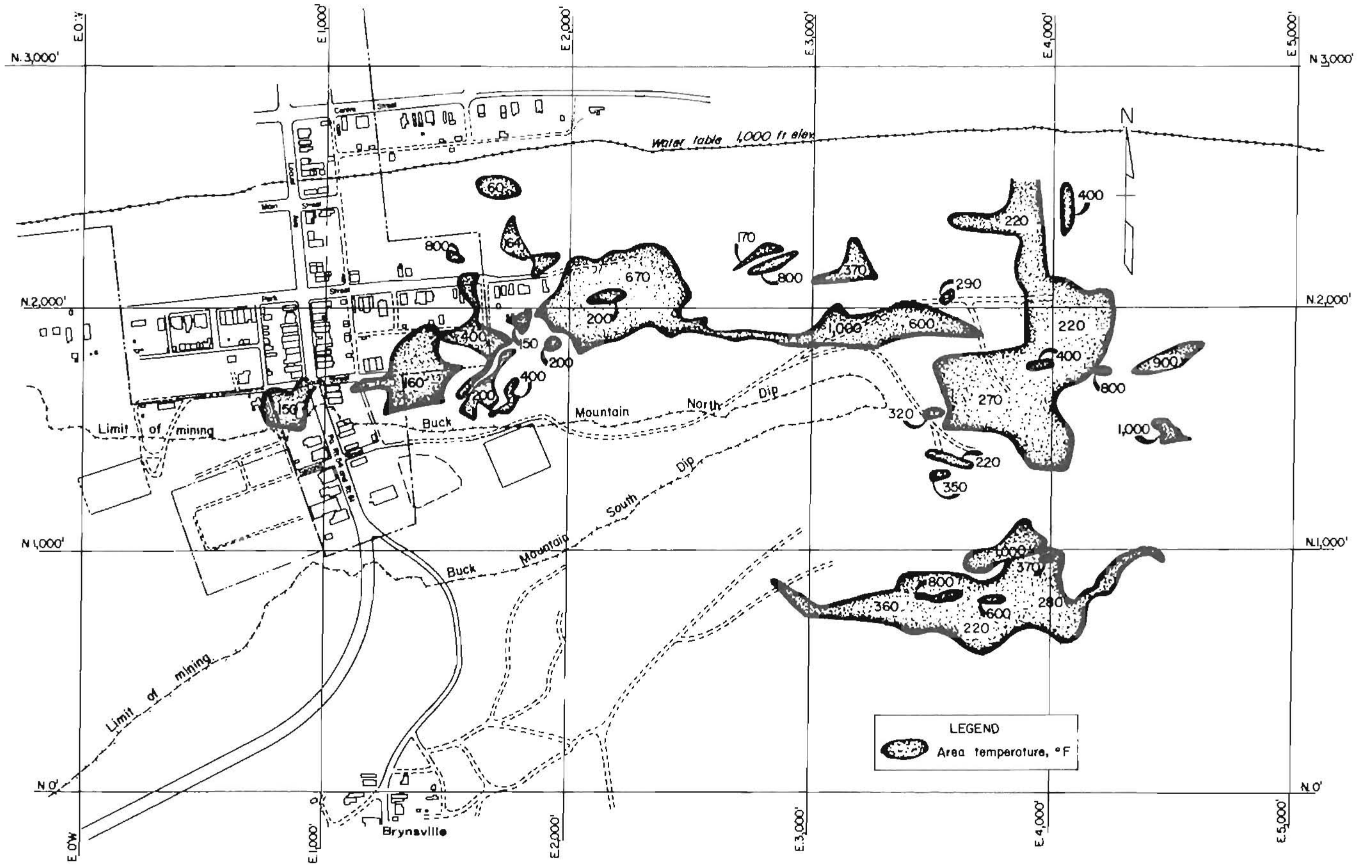
E.0'
E.1,000'
E.2,000'
E.3,000'
E.4,000'
E.5,000'
N.3,000'
N.2,000'
N.1,000'
N.0'
N
Centre Street
Main Street
Park Street
Water table 1,000 ft elev.
60
164
800
670
200
170
800
370
220
400
290
1,000
600
220
400
900
800
270
1,000
320
220
350
400
150
200
160
400
150
Limit of mining
Buck Mountain North Dip
Buck Mountain South Dip
1,000
370
800
360
280
600
220
LEGEND
Area temperature, °F
Limit of mining
Brynsville

FIGURE 17. - Underground temperature data indicating fire areas and "cold" zones.

EXTENT OF THE FIRE

Before fire control plans could be formulated for Centralia, it was necessary to establish the areal extent and depth of the fire, which, in turn, determined the location and magnitude of control efforts. This was accomplished by thermal mapping of borehole temperature readings to show the location of areas of elevated temperature. In the course of previous fire control efforts at Centralia, 1,800 boreholes have been drilled into the Seven Foot, Skidmore, and Buck Mountain Coalbeds. The temperature, CO concentration, and ventilation draft data recorded from these boreholes represent the only "hard" information related to the underground fire situation. These data (3,400 readings over a time span of 14 years) were taken from all previous reports (18-20), as well as recorded as recently as June 1980. The two approaches used to map the zones of elevated temperatures are plotting of borehole temperature data points on surface and underground maps and computerized mapping to generate isothermal contours over the surface of the fire area. A detailed description of methods used to assess the extent of an underground fire is given in appendix A.

By plotting the temperature data on surface and underground maps, it was established that the fire affects an area equivalent to 140 surface acres (figs. 18, 19). The fire has reached a depth of at least 300 feet below the surface (1,240-foot elevation) in the north dip of the Buck Mountain Seam, and 200 feet below the surface (1,200-foot elevation) on the south dip of the Locust Run section. The boundaries for the zones are based on the most recent data, and the interior temperatures and general shape of the zones are interpreted from all the temperatures recorded for the zone and from the local geometry of the Buck Mountain Seam (i.e., location of entries, tunnels, pillars, pitch of seam, etc.).

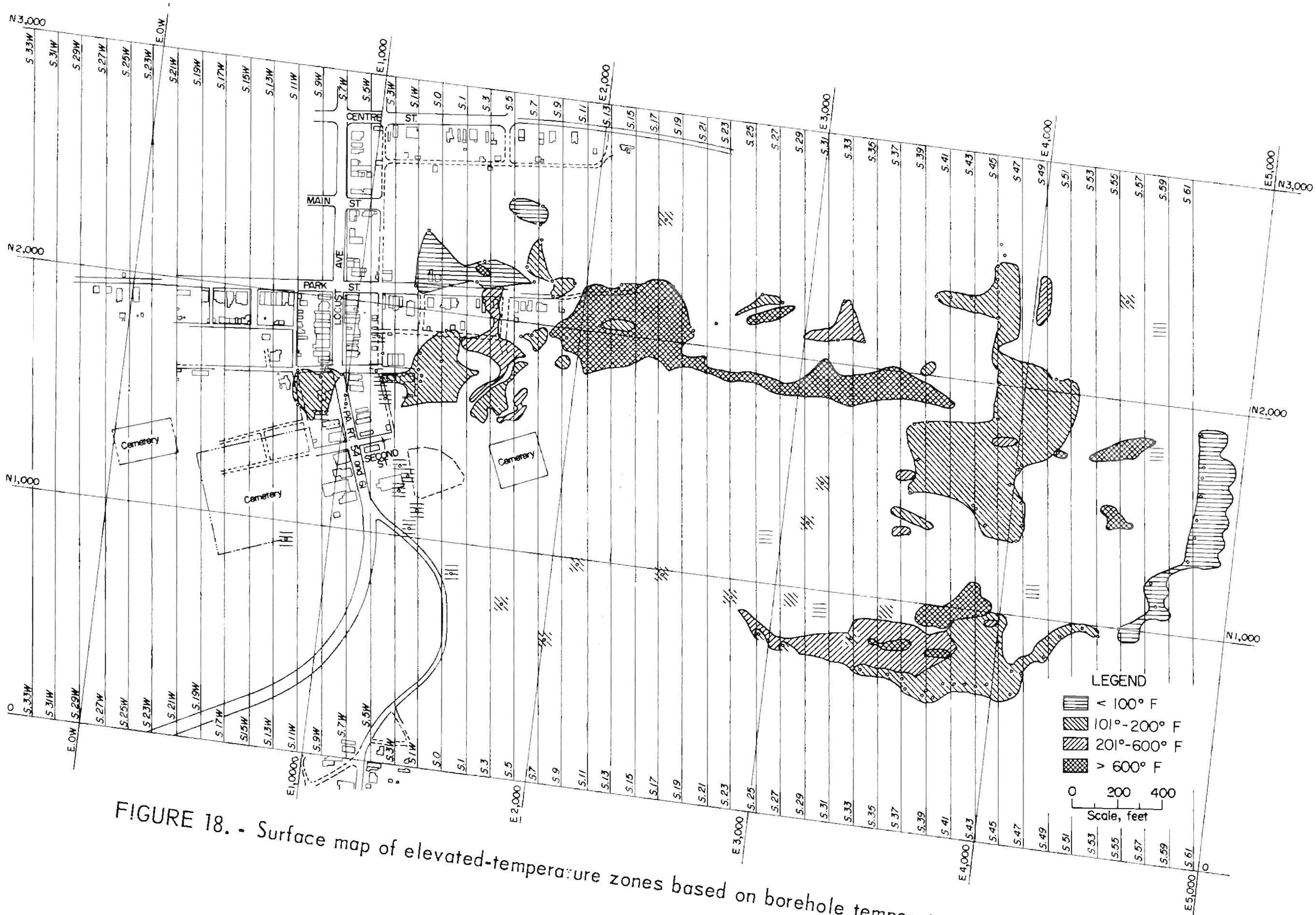
N3,000
N2,000
N1,000
0
E.0W
E1,000
E2,000
E3,000
E4,000
E5,000
S.33W
S.31W
S.29W
S.27W
S.25W
S.23W
S.21W
S.19W
S.17W
S.15W
S.13W
S.11W
S.9W
S.7W
S.5W
S.3W
S.1W
S.0
S.1
S.3
S.5
S.7
S.9
S.11
S.13
S.15
S.17
S.19
S.21
S.23
S.25
S.27
S.29
S.31
S.33
S.35
S.37
S.39
S.41
S.43
S.45
S.47
S.49
S.51
S.53
S.55
S.57
S.59
S.61
CENTRE
ST.
MAIN
ST.
AVE.
PARK
ST.
LOCUST
PA. RT.
SECOND
ST.
Cemetery
Cemetery
Cemetery
LEGEND
< 100° F
101°-200° F
201°-600° F
> 600° F
0
200
400
Scale, feet

FIGURE 18. - Surface map of elevated-temperature zones based on borehole temperature data.

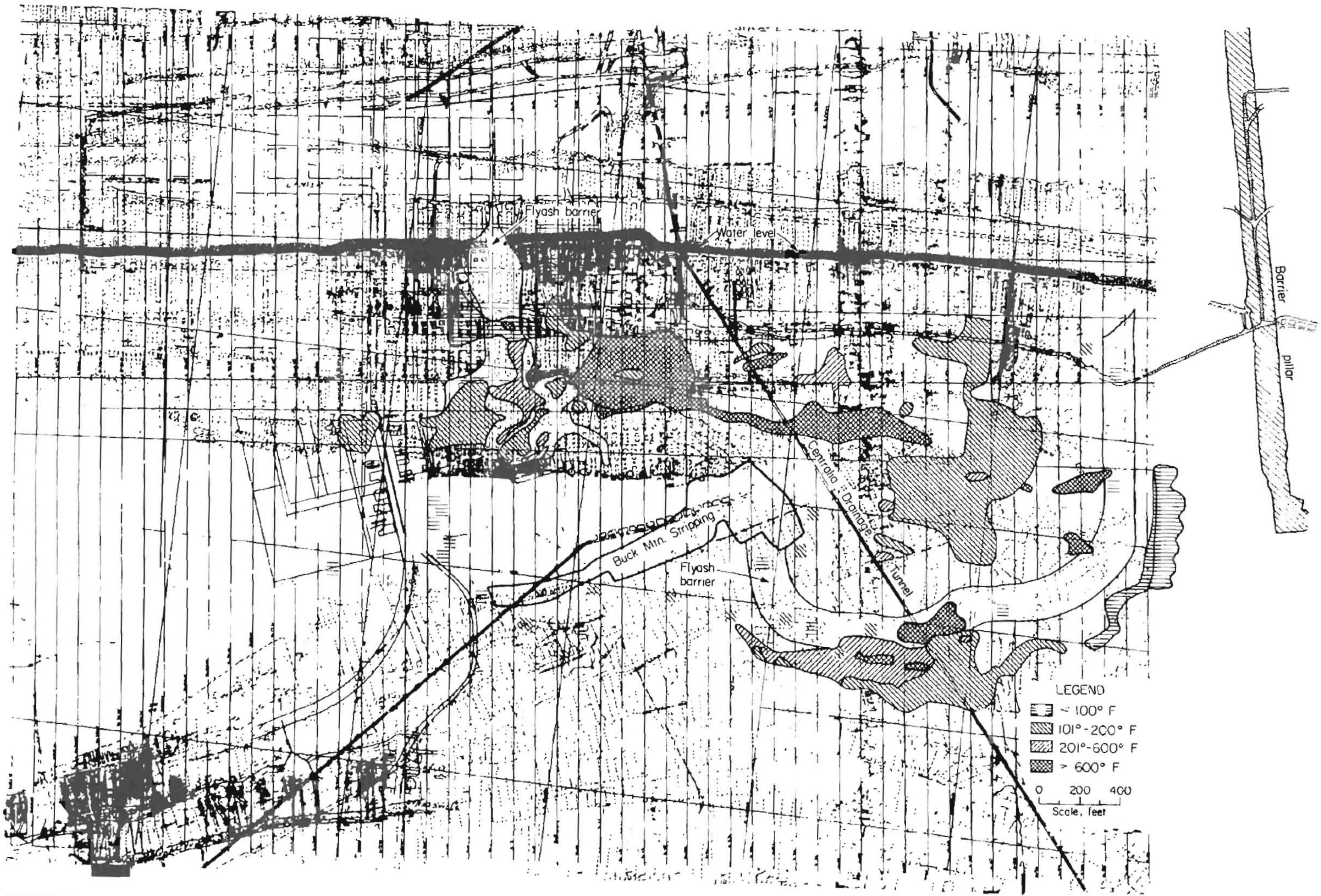
Flyash barrier
Water level
Barrier pillar
Centralia Drainage Tunnel
Buck Mtn. Stripping
Flyash barrier
LEGEND
< 100° F
101°-200° F
201°-600° F
> 600° F
0 200 400
Scale, feet

FIGURE 19. - Mine map of the Buck Mountain Coalbed in the area of the Centralia mine fire, showing zones of elevated temperature.

No attempt was made to extrapolate the elevated temperatures beyond the immediate area of the borehole locations. Extrapolations were made only for bounding the zone.

High-temperature zones are separated by cooler zones, indicating spread of the fire by circulation of hot gases. The fire has spread more rapidly to the east than to the west, and it has moved across the anticline in the eastern area. It is currently spreading along the south dip toward the village of Byrnsville, and also toward the drainage tunnels situated east of the borough. The flush barrier along the western side of the fire area has been breached by hot fumes, and conditions favoring spontaneous combustion may already exist under the area near Locust Street.

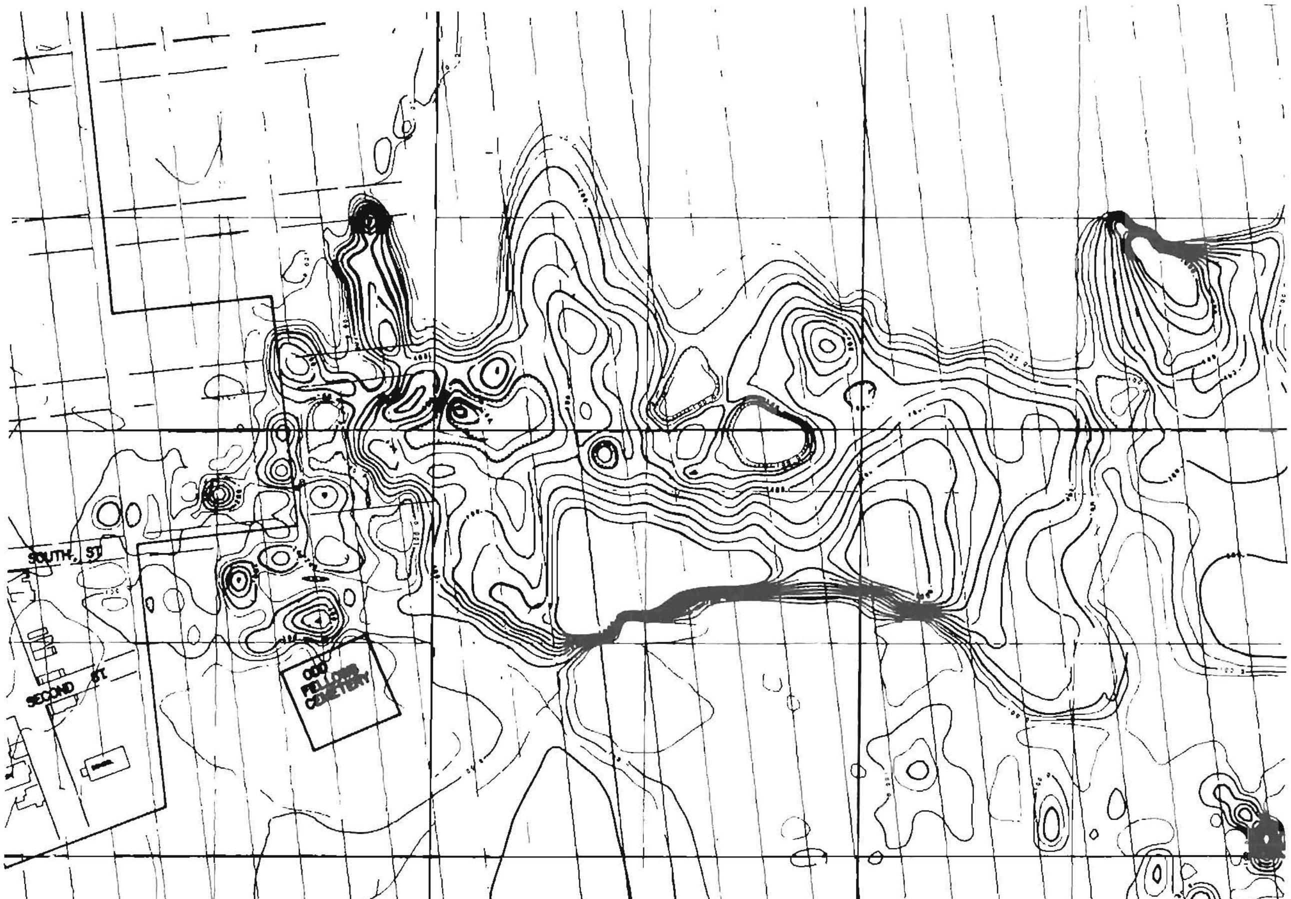

FIGURE 20. - Computer-generated thermal contour map based on borehole temperature data collected 1967-79.

At present (i.e., data up to 1980), there is no positive evidence that the fire has reached the seams above the Buck Mountain. All the valid temperatures in the Seven Foot and Skidmore seams have been cold (55° to 65° F). Although the data do not indicate the presence of fire in these seams, there is a likelihood that they will eventually catch fire if the Buck Mountain Seam fire continues.

The high-temperature isotherms generated by the computerized mapping program are strikingly similar to the high-temperature zones plotted from borehole data (fig. 20). The basic difference between the two types of mapping is that the computer program extrapolates data to areas far removed from the location of the boreholes.

EFFECTS OF THE FIRE[9]

Today Centralia is comprised of about 500 homes, four churches, public buildings, and businesses (fig. 21). The population is approximately 1,200. Of these, 310 structures and approximately 500 people are in the area currently or potentially affected by the Centralia mine fire.

For the town's residents, the most immediate effect of the underground fire has been the combustion gases that have penetrated area homes. Gases were first discovered in 1969 when CO, excess CO_2, and O_2 deficiency were detected in several homes in the borough, and residents had to be temporarily evacuated. When gases again became a problem in 1979, monitors provided by the U.S. Department of the Interior were placed in 15 area homes. Analysis of bottle samples of air taken in the living area of homes has revealed CO_2 levels of less than 0.5 pct, while some basement floor areas have approached 1 pct CO_2 (See appendix B.) An exception is the basement floor of residence C, where CO_2 levels as high as 10 pct have been recorded; readings up to 1 to 2 ppm CO have been recorded.

Fumes and a lack of oxygen in area homes have been an especially serious problem for area residents with chronic respiratory ailments. In an effort to carry sulfurous fumes above breathing space, pipes have been installed extending upward over the openings in the ground through which gases are escaping.

Another hazard presented by the fire is the danger of surface subsidence. As the fire consumes the coal below, surface subsidence can result, particularly where underground coal pillars supporting the roof are destroyed. Several incidences of subsidence have occurred in the fire area. In some cases, however, subsidence may simply be a result of the previous underground mining, and not the fire.

A third problem has been the concern about elevated ground temperatures as a result of the fire. A local gasoline station was closed in December 1979 due to fumes and concern that the high ground temperature made it unsafe to store gasoline in the underground tanks.

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[9] The Centralia mine fire has been covered extensively by the press. Detailed reports on the effects of the fire have been given in the Pottsville Republican; the Citizen's Voice, Wilkes-Barre, PA; the Hazelton Standard Speaker; The News-Item, Shamokin, PA; The Scranton Times; the Evening Herald, Ashland, PA; The Philadelphia Inquirer; The Pittsburgh Press; The Pittsburgh Post-Gazette; and The New York Times.

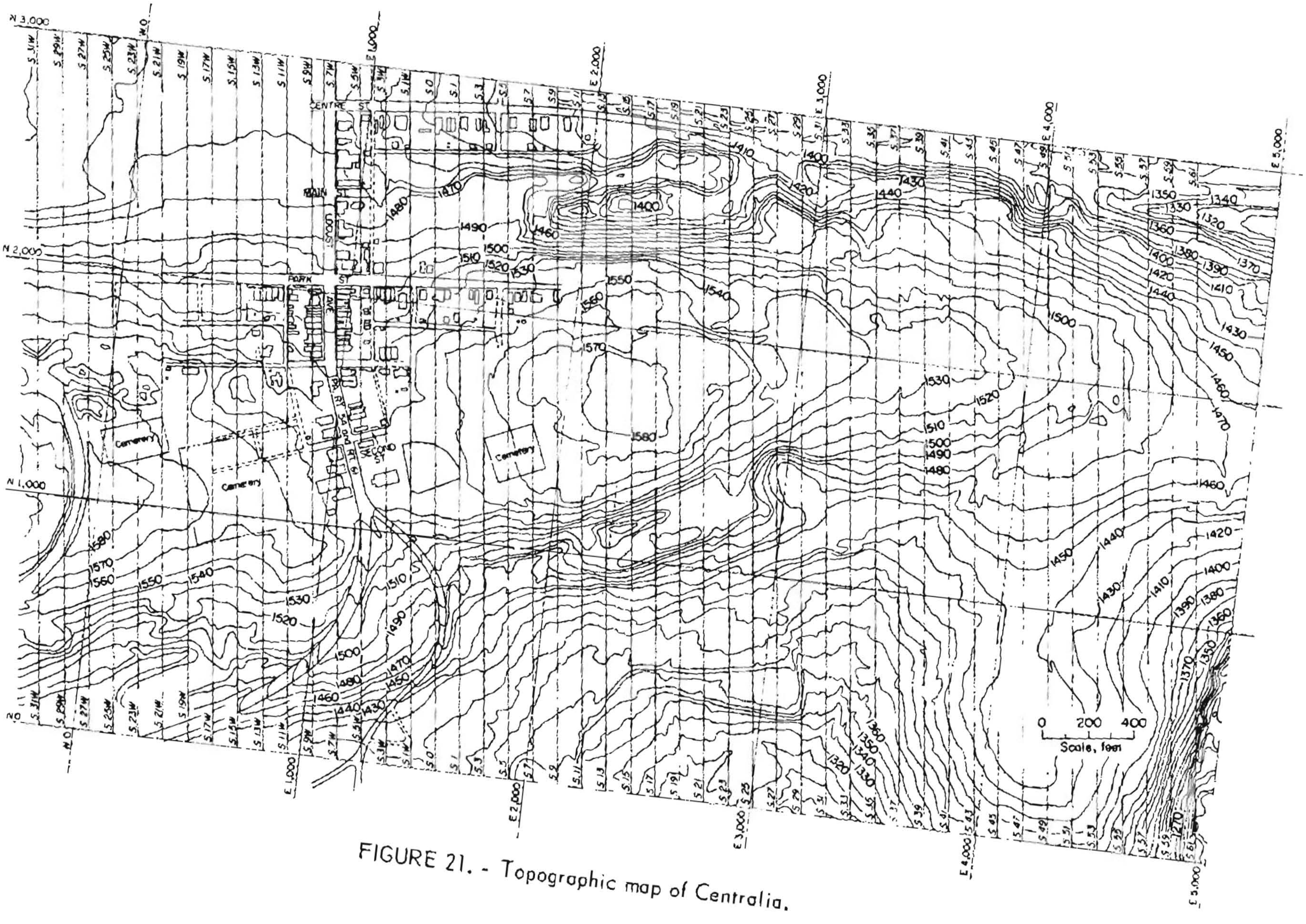
N 3,000
N 2,000
N 1,000
N 0
W 0
E 1,000
E 2,000
E 3,000
E 4,000
E 5,000
S 31W
S 29W
S 27W
S 25W
S 23W
S 21W
S 19W
S 17W
S 15W
S 13W
S 11W
S 9W
S 7W
S 5W
S 3W
S 1W
S 0
S 1
S 3
S 5
S 7
S 9
S 11
S 13
S 15
S 17
S 19
S 21
S 23
S 25
S 27
S 29
S 31
S 33
S 35
S 37
S 39
S 41
S 43
S 45
S 47
S 49
S 51
S 53
S 55
S 57
S 59
S 61
CENTRE ST
MAIN ST
LOCUST AVE
PARK ST
PA. RY 54 and RT 61
SECOND ST
Cemetery
Cemetery
Cemetery
1580
1570
1560
1550
1540
1530
1520
1510
1500
1490
1480
1470
1460
1450
1440
1430
1420
1410
1400
1390
1380
1370
1360
1350
1340
1330
1320
1270
0
200
400
Scale, feet

FIGURE 21. - Topographic map of Centralia.

OPTIONS FOR FIRE CONTROL AT CENTRALIA

This report has discussed anthracite mine fire control measures in general, and assessed the situation for a specific anthracite mine fire at Centralia. In order to have a better idea of the practical application, technical feasibility, effectiveness, and costs of available fire control options in an actual fire situation, this section will examine the fire control options as they would apply specifically to Centralia.[10]

In any fire control project, whatever control measures are to be applied, the first step is to assess the extent of the fire. In the case of Centralia, this involves refining and updating the temperature map. Despite the large number of boreholes drilled into the fire area and the 3,400 data points obtained from these holes, additional drilling would be needed to establish the exact extent and depth of the hot zone (i.e., temperature >200° F), and to define the western and southern "cold" boundaries. Any positive approach to fire control at Centralia must start in the cold boundary, not in an elevated temperature zone. The locations of both the cold boundary and the known fire areas are important in establishing the magnitude of the control project as well as refining the basic approach to be used. It is estimated that 41 new boreholes would be required on the north dip of the Centralia Mine, and 44 new boreholes on the south dip of the Locust Run section. At $25 per foot for drilling and casing, the 1980 estimate of the cost of the assessment boreholes alone is $500,000. In addition to this are the costs of monitoring the boreholes, including the data gathering, reduction, and interpretation. This assessment and monitoring work is a requirement for essentially any of the options that are considered. The same boreholes also serve as fire-monitoring stations during and after implementation of a fire control program.

EXCAVATION OPTIONS

The review of conventional methods of controlling anthracite mine fires indicates that excavation is the most consistently successful approach to extinguishing and/or controlling underground fires. For this reason, four possible excavation plans have been formulated for the Centralia fire:

Plan A--Totally excavating and quenching the fire area.

Plan B--Excavating a cutoff trench to prevent the spread of fire.

Plan C--Excavating isolation trenches to confine the fire within a restricted area.

Plan D--A combination of the above.

Figures 18 and 19 show the surface and underground areas of known elevated temperature. It is assumed for the purposes of developing detailed excavation plans that the present area affected by the fire (484 acres on the surface and 395 acres underground) is the area to be considered in the excavation plans. Refining the temperature map to more accurately establish the cold boundary might alter these dimensions.

The four excavation plans were evaluated for feasibility, advantages, disadvantages, costs, hazards, and length of time each project would take. A summary of the time-frame requirements for each plan (table 4) indicates that the time required has a relatively minor effect on the total cost. The daily excavation rate is a factor as it determines the size and amount of equipment required. All pertinent technical data and cost estimates are compared in table 5. A breakdown of the project work and the cost data for each plan for the north dip of the coalbed and the south dip is given in appendix C.

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[10] Costs are figured in 1980 dollars, and are estimates provided solely for the purpose of comparing the various fire control options.

TABLE 4. - Time-frame, daily excavation, and yearly budget requirements for plans A, B, C, and D

Years of contract	Plan A	Plan B	Plan C	Plan D
BUDGET, MILLION DOLLARS PER YEAR				
4....................	21.0	10.3	5.5	8.13
6....................	14.0	6.8	3.6	5.5
8....................	10.5	5.1	2.8	4.1
10...................	8.4	4.1	2.2	3.2
Total expenditure, million dollars......	84	41	22	32
EXCAVATION M CU YD/DAY				
4....................	33.1	15.1	6.1	11.3
6....................	22.0	9.8	3.7	7.5
8....................	16.6	7.5	3.0	5.6
10...................	13.2	6.0	2.4	4.5
Total yardage removed, MM cu yd............	35,000	16,000	6,500	12,000

TABLE 5. - Comparison of technical and financial data for excavation method

	Plan A	Plan B	Plan C	Plan D
Project area..............................acres..	140.0	89.3	36.0	64.3
Depth of excavation.........................ft..	200-300	200-300	200-540	200-540
Isolation-fire area remaining.............acres..	0	50.6	151.0	76.6
Structures destroyed............................	109	109	134	112
Project start time..............................	Delay	Delay	Delay	Delay
Project work:				
Excavation.........................MM cu yd..	35.0	15.8	6.4	12.0
Backfill...........................MM cu yd..	24.5	11.0	4.5	8.5
Quenching..........................MM cu yd..	14.0	4.4	1.0	4.8
Coal recovery..................thousand tons..	1,158.0	452.0	56.7	345.8
Drill holes..................................	85.0	85.0	85.0	85.0
Cost, million dollars:				
Drilling.....................................	0.4	0.4	0.4	0.4
Excavation at $2.25/cu yd....................	78.7	35.5	14.4	27.1
Backfilling at $1.00/cu yd...................	24.5	11.0	4.5	8.5
Quenching....................................	.3	.3	.3	.3
Property value at $30,000 per structure........	3.3	3.3	4.0	3.4
Total..................................	107.2	50.5	23.6	39.7
Coal recovery at $20/ton.................	23.1	9.0	1.1	6.9
Total..................................	84.1	41.5	22.5	32.8

Total Excavation of the Fire Area (Plan A)

A total excavation of the high-temperature area (>200° F) (figs. 22-24) would involve excavating to a depth of 300 feet on the north dip of the Buck Mountain Coalbed, which involves approximately 83 acres, and excavating on the south dip to a depth of 200 feet, which involves approximately 57 acres. The excavation of a total of 140 surface acres would require the destruction of 109 structures.

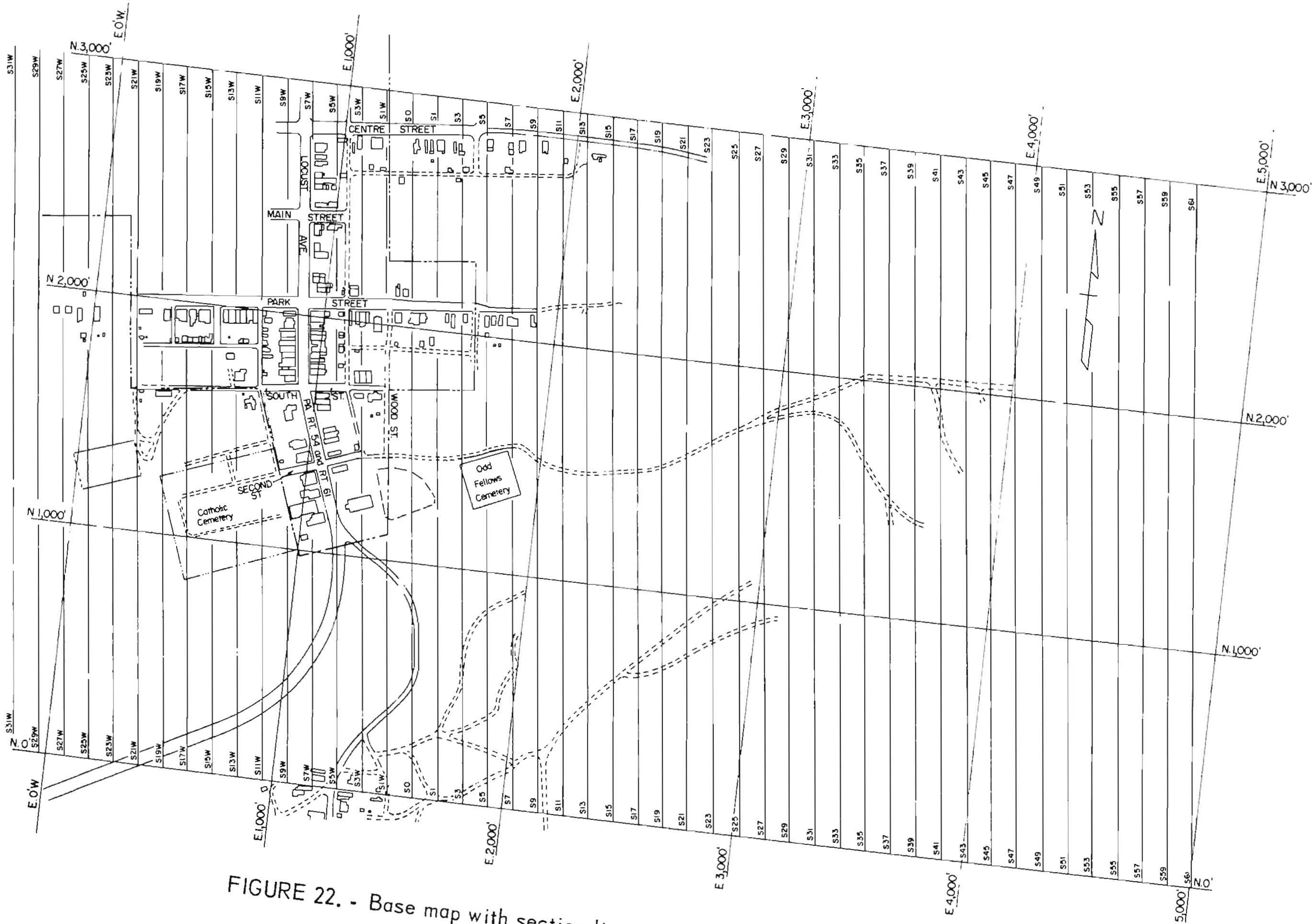

N.3,000'
N.2,000'
N.1,000'
N.0'
E.0'W.
E.1,000'
E.2,000'
E.3,000'
E.4,000'
E.5,000'
S31W
S29W
S27W
S25W
S23W
S21W
S19W
S17W
S15W
S13W
S11W
S9W
S7W
S5W
S3W
S1W
S0
S1
S3
S5
S7
S9
S11
S13
S15
S17
S19
S21
S23
S25
S27
S29
S31
S33
S35
S37
S39
S41
S43
S45
S47
S49
S51
S53
S55
S57
S59
S61
N
CENTRE STREET
LOCUST AVE.
MAIN STREET
PARK STREET
SOUTH ST.
WOOD ST.
PA. RT. 54 and RT. 61
SECOND ST.
Catholic Cemetery
Odd Fellows Cemetery

FIGURE 22. - Base map with section lines for locating cross sections.

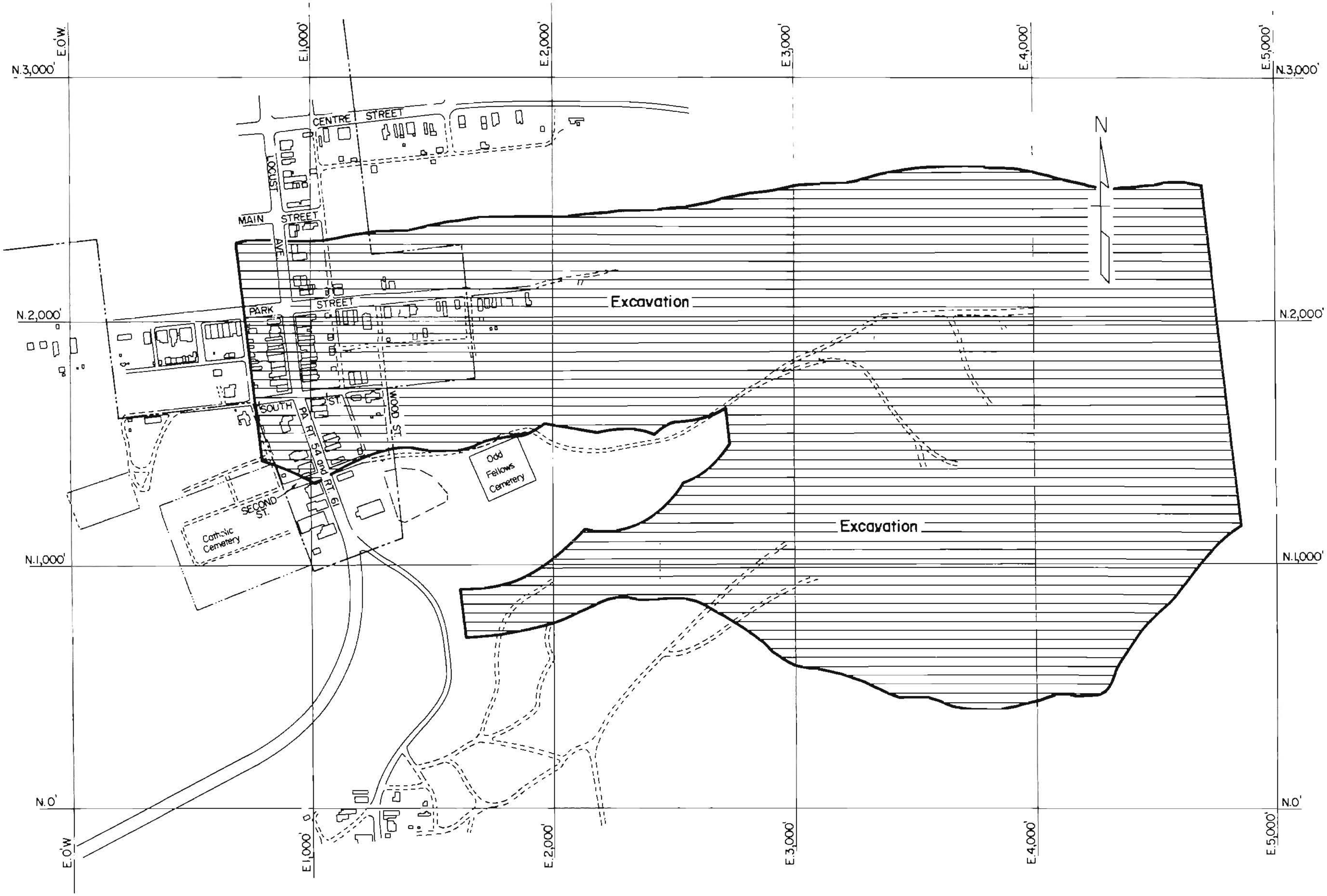

N.3,000'
N.2,000'
N.1,000'
N.0'
E.0'W.
E.1,000'
E.2,000'
E.3,000'
E.4,000'
E.5,000'
N
CENTRE STREET
LOCUST STREET
MAIN AVE
PARK STREET
SOUTH ST.
WOOD ST.
PA RT. 54 and RT. 61
SECOND ST.
Catholic Cemetery
Odd Fellows Cemetery
Excavation
Excavation

FIGURE 23. - Proposed total excavation of Centralia mine fire, plan A.

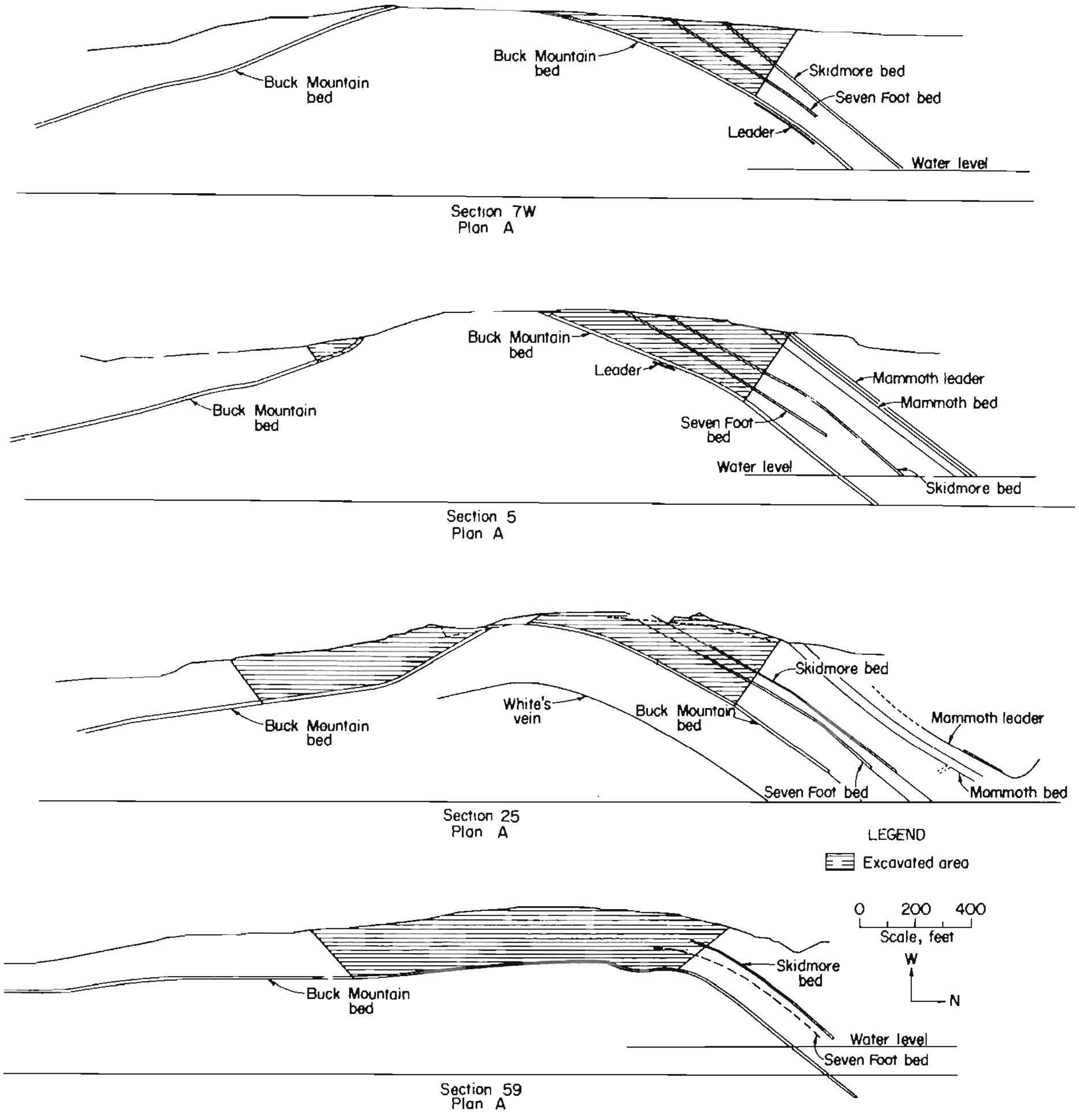

Buck Mountain bed
Buck Mountain bed
Skidmore bed
Seven Foot bed
Leader
Water level
Section 7W
Plan A
Buck Mountain bed
Leader
Mammoth leader
Mammoth bed
Buck Mountain bed
Seven Foot bed
Water level
Skidmore bed
Section 5
Plan A
Skidmore bed
White's vein
Buck Mountain bed
Mammoth leader
Buck Mountain bed
Seven Foot bed
Mammoth bed
Section 25
Plan A
LEGEND
Excavated area
0 200 400
Scale, feet
W
N
Skidmore bed
Buck Mountain bed
Water level
Seven Foot bed
Section 59
Plan A

FIGURE 24. - Cross sections through area of plan A.

From the summary of the project work and costs shown in table 5, this plan is clearly much more extensive than are the other three. Its advantages are that it has the highest probability of successfully extinguishing the fire, and no isolated fire area would be left to burn itself out. Also, the project surface area would be made usable for future community development. The disadvantages of the total excavation plan are (1) the extremely high total project cost ($84 million), (2) the destruction of 109 structures in the town of Centralia, (3) the relocation of State Highway Route 61, (4) the relocation of a natural gas line and surface utility lines, (5) 6-year plan for excavation would require equipment capable of excavating 22,000 cu yd/day and an annual budget of $14 million; and (6) the time required to obtain title to the properties could delay the start of the project, allowing the fire to spread further and resulting in higher costs.

Partial Excavation With Isolation Trench (Plan B)

The Partial Excavation-Isolation Trench (plan B) uses total excavation to extinguish the part of the fire under the borough and trench excavation to isolate the part of the fire that underlies unpopulated areas (figs. 25-26). This would involve total excavation of the high-temperature area on the north dip. The excavated area on the western side would be 1,400 feet long and 300 feet deep. The northern and southern isolation trenches would be 2,400 to 2,600 feet long, to a depth of 300 feet. The eastern isolation trench would be 1,800 feet long, to a depth of 300 feet. The isolation trenches will be 50 feet wide at coalbed.

The project area would encompass 60 acres on the north dip and 29 acres on the south dip. Of this total 89 acres, a 51-acre fire area would remain after completion of the project. Excavation on the north dip would require the destruction of 109 structures.

The advantages of plan B are that the cost would be less than 50 pct that of plan A (as shown in the summary of project work and costs in table 5), and the high-temperature area within the borough limits would still be removed. The disadvantages are (1) relatively high total project cost ($42 million), (2) destruction of 109 structures in the town of Centralia, (3) the relocation of State Highway Route 61, (4) the relocation of a natural gas line and surface utility

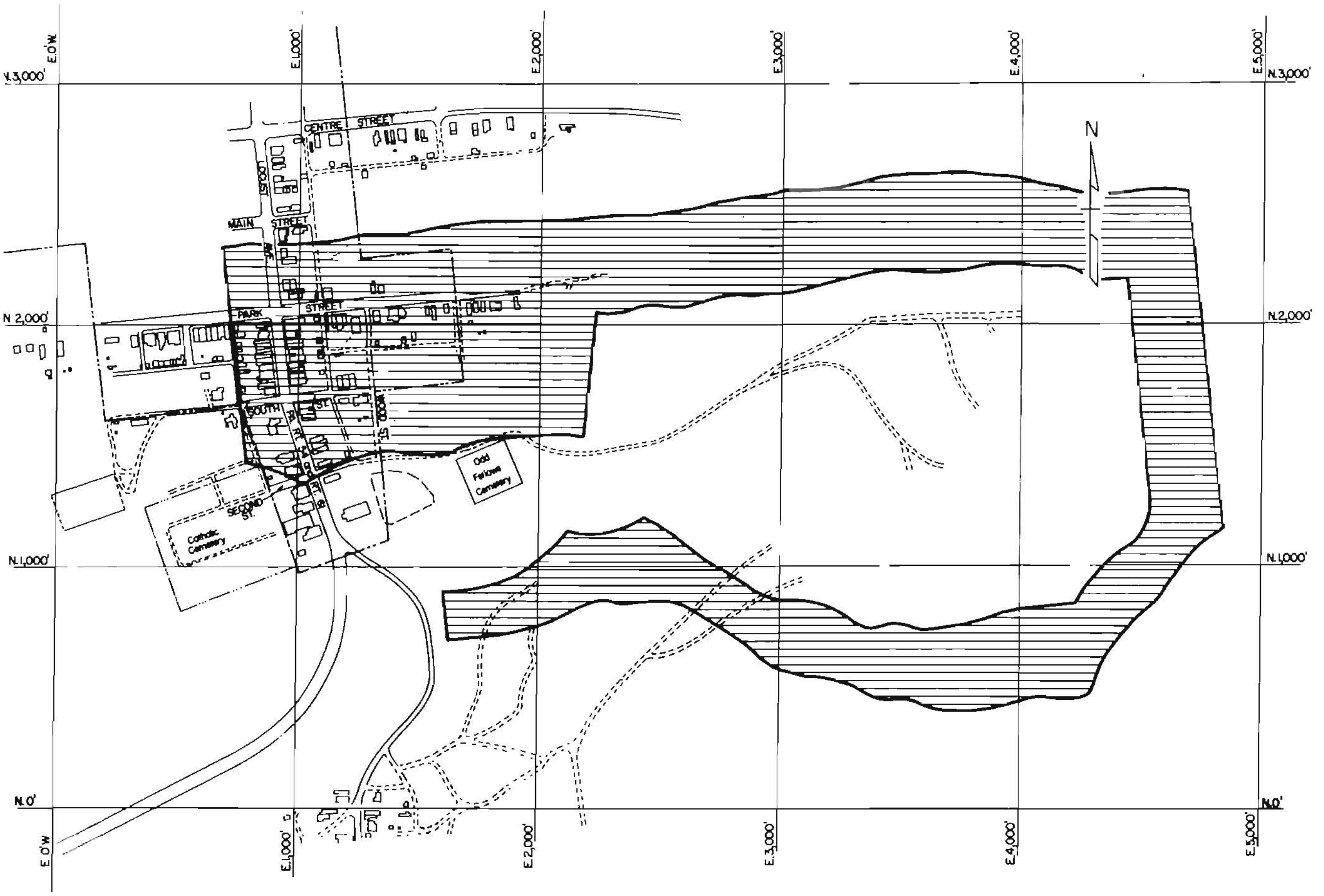


FIGURE 25. - Proposed partial excavation with isolation trench, plan B.

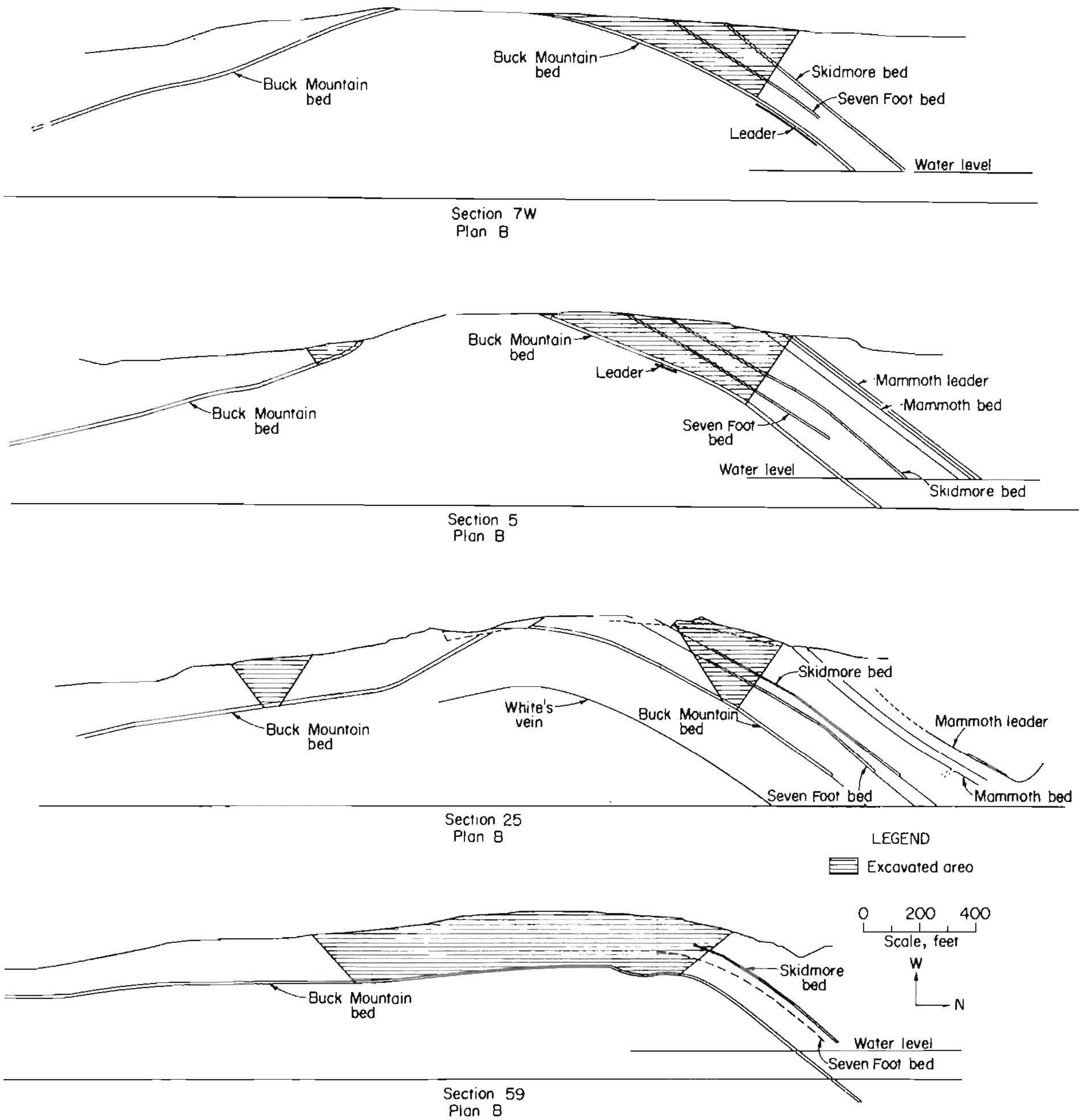

Buck Mountain bed
Buck Mountain bed
Skidmore bed
Seven Foot bed
Leader
Water level
Section 7W
Plan B
Buck Mountain bed
Leader
Buck Mountain bed
Mammoth leader
Mammoth bed
Seven Foot bed
Water level
Skidmore bed
Section 5
Plan B
Skidmore bed
White's vein
Buck Mountain bed
Mammoth leader
Buck Mountain bed
Seven Foot bed
Mammoth bed
Section 25
Plan B
LEGEND
Excavated area
0 200 400
Scale, feet
W
N
Skidmore bed
Buck Mountain bed
Water level
Seven Foot bed
Section 59
Plan B

FIGURE 26. - Cross sections through area of plan B.

lines, (5) the potential problems created by isolating 51 acres of underground fire located within 1,500 feet of the residential area, (6) the potential future fire hazards created by the unexcavated area (350 feet) from the bottom of the isolation trench on the north dip to water level, (7) a 6-year plan for excavation would require equipment capable of excavating 9,800 cu yd/day and a yearly budget of $6.8 million, and (8) obtaining title to the involved properties could delay the start of the project, allowing the fire to spread and resulting in higher costs.

Combination Cutoff and Isolation Trench (Plan C)

This excavation trench scheme is designed to isolate the fire within the existing natural boundaries (figs. 27-28). This would involve excavation of a cutoff trench on the north dip, from the outcrop north 1,100 feet to the water level at a depth of 540 feet, and an isolation trench on the south dip, 200 feet deep and 2,600 feet long.

The project would include 12 acres on the north dip and 24 acres on the south dip. Within the total 36 acres, 134 structures would be destroyed on the north dip. Upon completion of the project, a fire area of 151 acres would remain.

The advantages of plan C are that the cost would be 75 pct less than plan A and 50 pct less than plan B, as shown in the summary of project work and costs in table 5. Also, the isolation trench on the south dip could be made a separate project from the cutoff trench on the north dip. The equipment requirements are substantially less as shown in table 4. A 6-year plan for excavation would require equipment capable of excavating

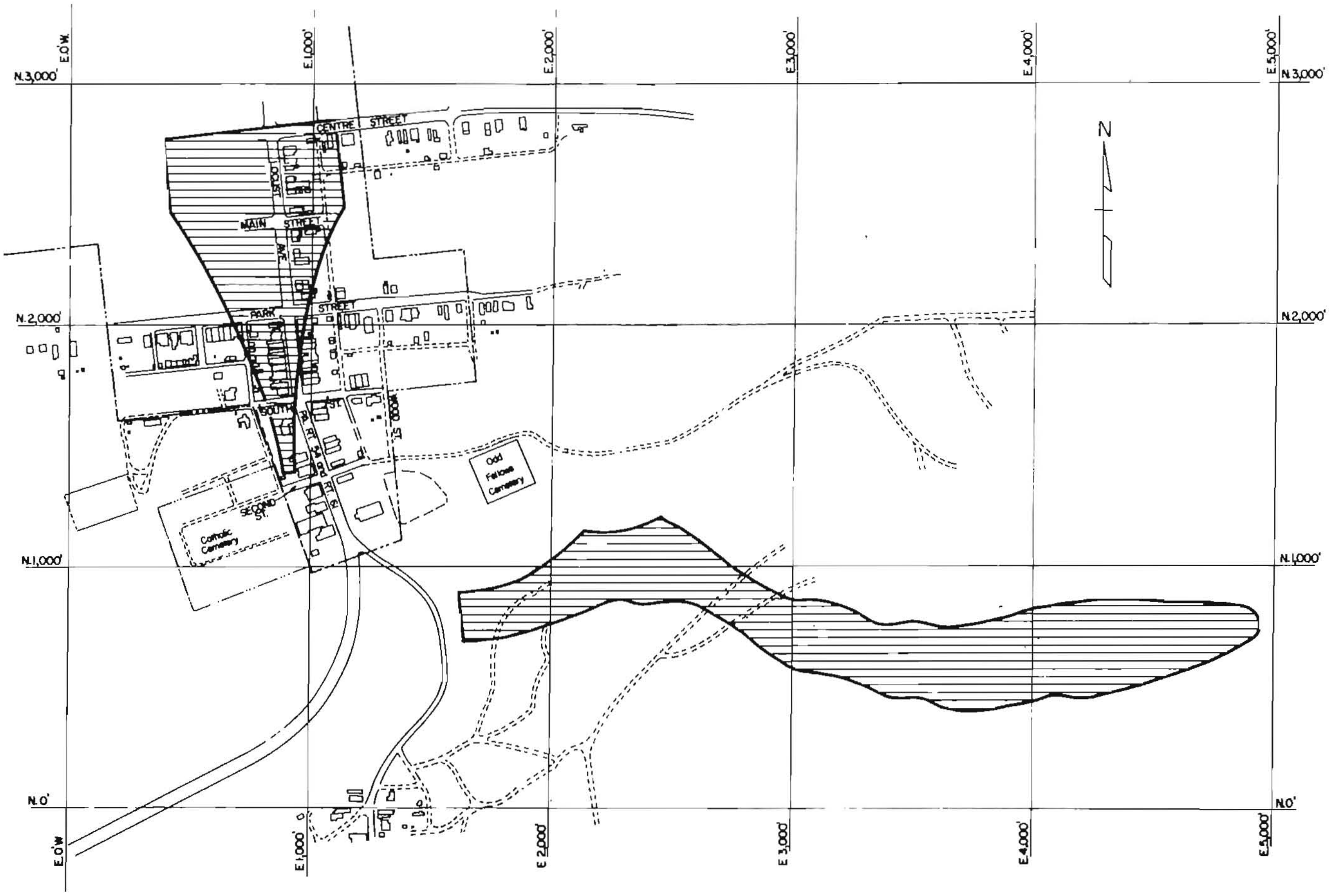

E.0'W.
E.1,000'
E.2,000'
E.3,000'
E.4,000'
E.5,000'
N.3,000'
N.2,000'
N.1,000'
N.0'
N
CENTRE STREET
MAIN STREET
LOCUST AVE.
PARK STREET
SOUTH ST.
SECOND ST.
Odd Fellows Cemetery
Catholic Cemetery

FIGURE 27. - Proposed combination cutoff and isolation trench, plan C.

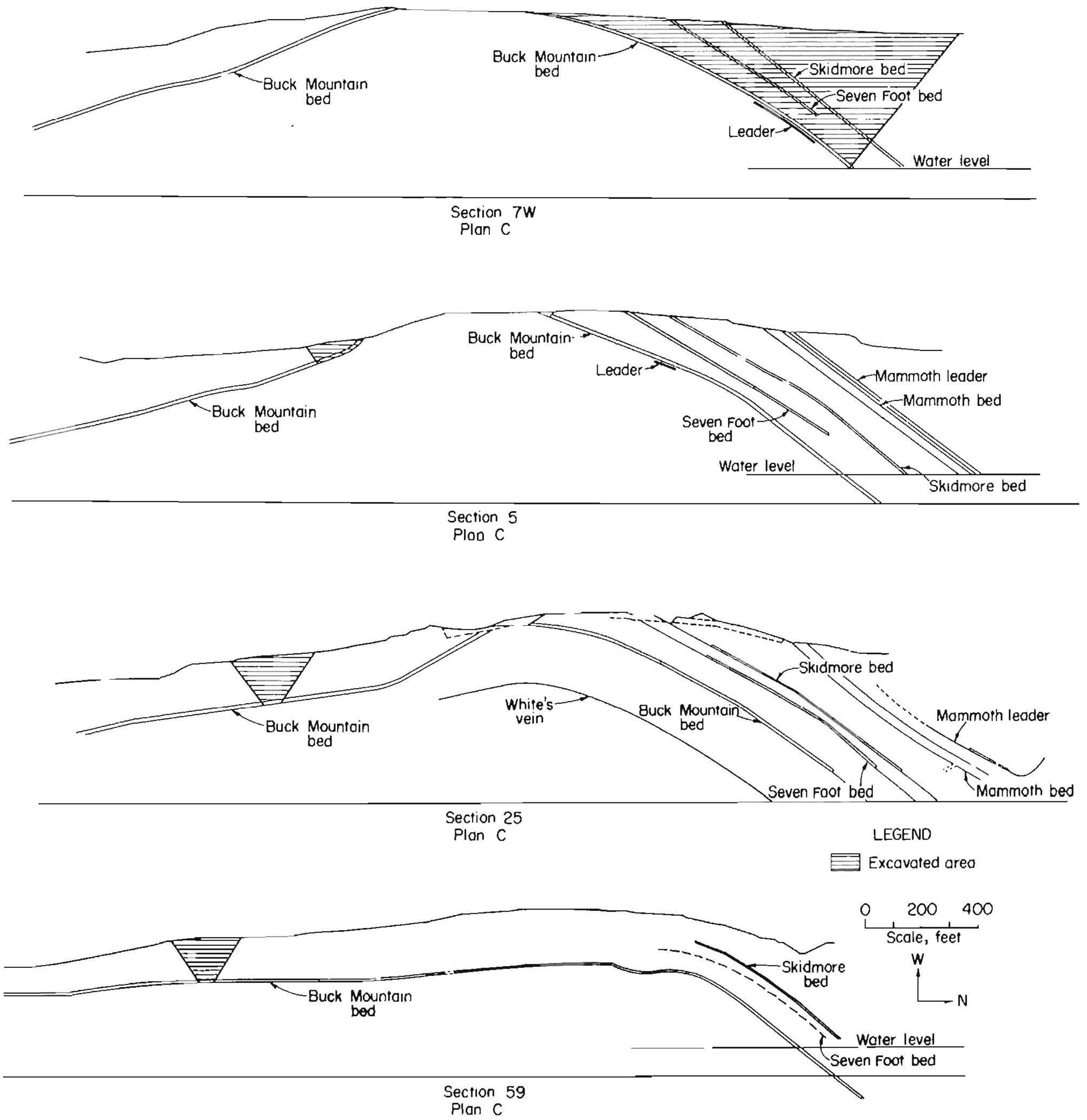

Buck Mountain bed
Buck Mountain bed
Skidmore bed
Seven Foot bed
Leader
Water level
Section 7W
Plan C
Buck Mountain bed
Leader
Buck Mountain bed
Mammoth leader
Mammoth bed
Seven Foot bed
Water level
Skidmore bed
Section 5
Plan C
Skidmore bed
White's vein
Buck Mountain bed
Buck Mountain bed
Mammoth leader
Seven Foot bed
Mammoth bed
Section 25
Plan C
LEGEND
▤ Excavated area
0 200 400
Scale, feet
W
N
Skidmore bed
Buck Mountain bed
Water level
Seven Foot bed
Section 59
Plan C

FIGURE 28. - Cross sections through area of plan C.

3,700 cu yd/day and an annual budget of $3.6 million. The disadvantages include (1) condemnation of 134 structures in the town of Centralia, (2) the relocation of State Highway Route 61, (3) the relocation of a natural gas line and surface utility lines, (4) the relocation of sanitary and surface drainage features, (5) the problems created by isolating 151 acres of underground fire within the borough boundary, and (6) obtaining title to the involved properties could delay the start of the project, allowing the fire to spread and resulting in higher costs.

Partial Excavation With Cutoff and Isolation Trench (Plan D)

This plan (figs. 29-30) is a combination of excavation plans B and C and minimizes some of the disadvantages of each. It involves total excavation of the high-temperature area on the north dip 1,400 feet long to a depth of 300 feet, a 400-foot cutoff trench to water level to a depth of 540 feet, and an isolation trench on the south dip 2,600 feet long to a depth of 200 feet.

The project would involve 40 acres on the north dip and 24 acres on the south dip. Within this 64-acre area, 112 structures would be destroyed. Upon completion of the project, a fire area of 77 acres would remain.

As shown in the summary of project work and costs in table 5, of the four excavation plans, only plan C is less costly. The advantages of plan D include the removal of the high-temperature area within the borough limits. Also the use of a cutoff trench on the north dip excavated to water level would destroy fewer homes than the trench in plan C. The isolation trench on the south dip could be made a separate project from the excavation on the north dip. The disadvantages include (1) the condemnation of 112 structures in the town of Centralia, (2) the relocation of State Highway Route 61, (3) the relocation of a natural gas line and surface utility lines, (4) the problems created by isolating 77 acres of underground fire within 1,500 feet of the residential area, (5) the relatively high total project costs ($32 million), (6) a 6-year plan for excavation would require equipment capable of excavating 7,500 cu yd/day and a yearly budget of $5.5 million, and (7) obtaining title to the involved properties could only delay the start of the project, allowing the fire to spread and resulting in higher costs.

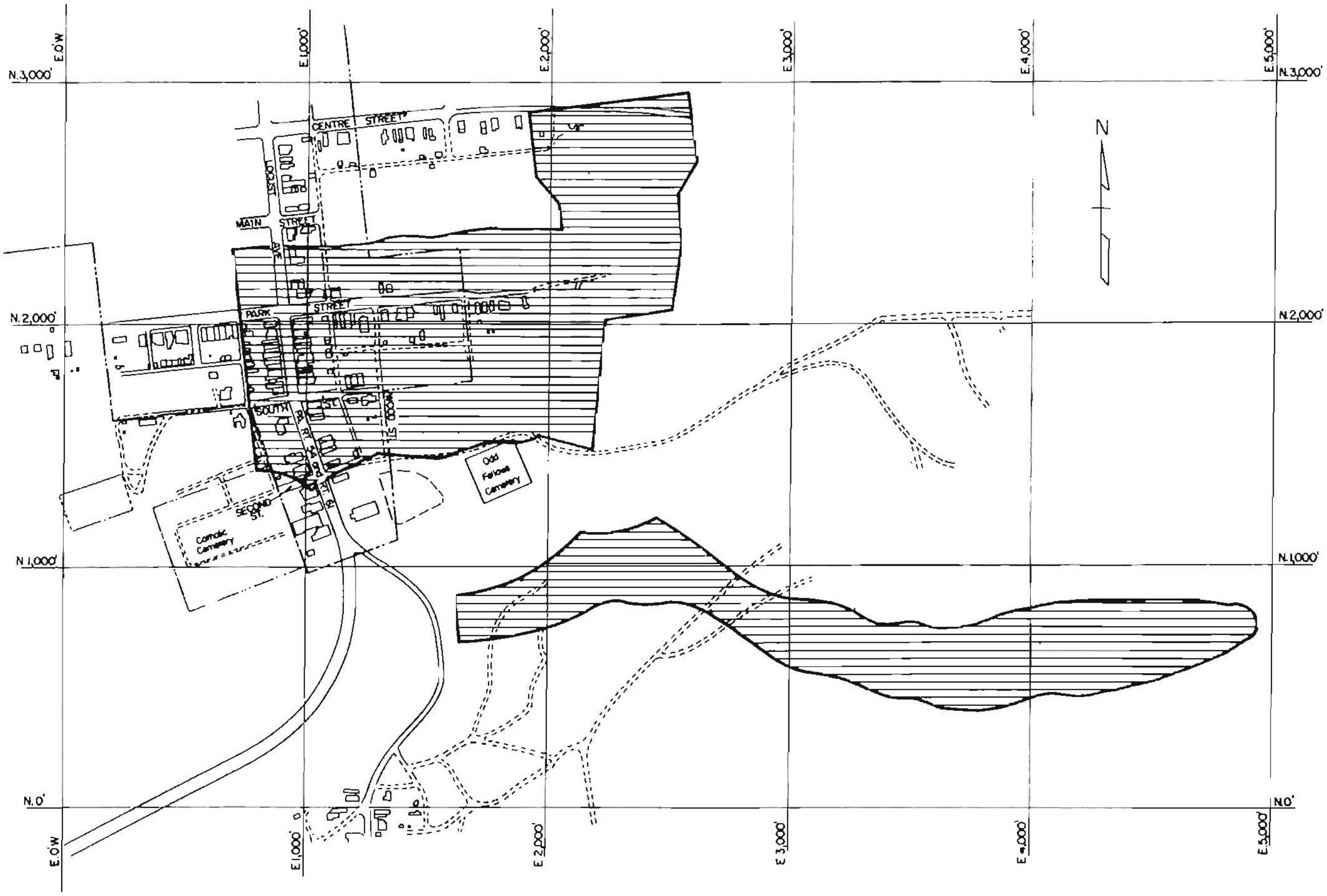


FIGURE 29. - Proposed excavation with cutoff and isolation trench, plan D.

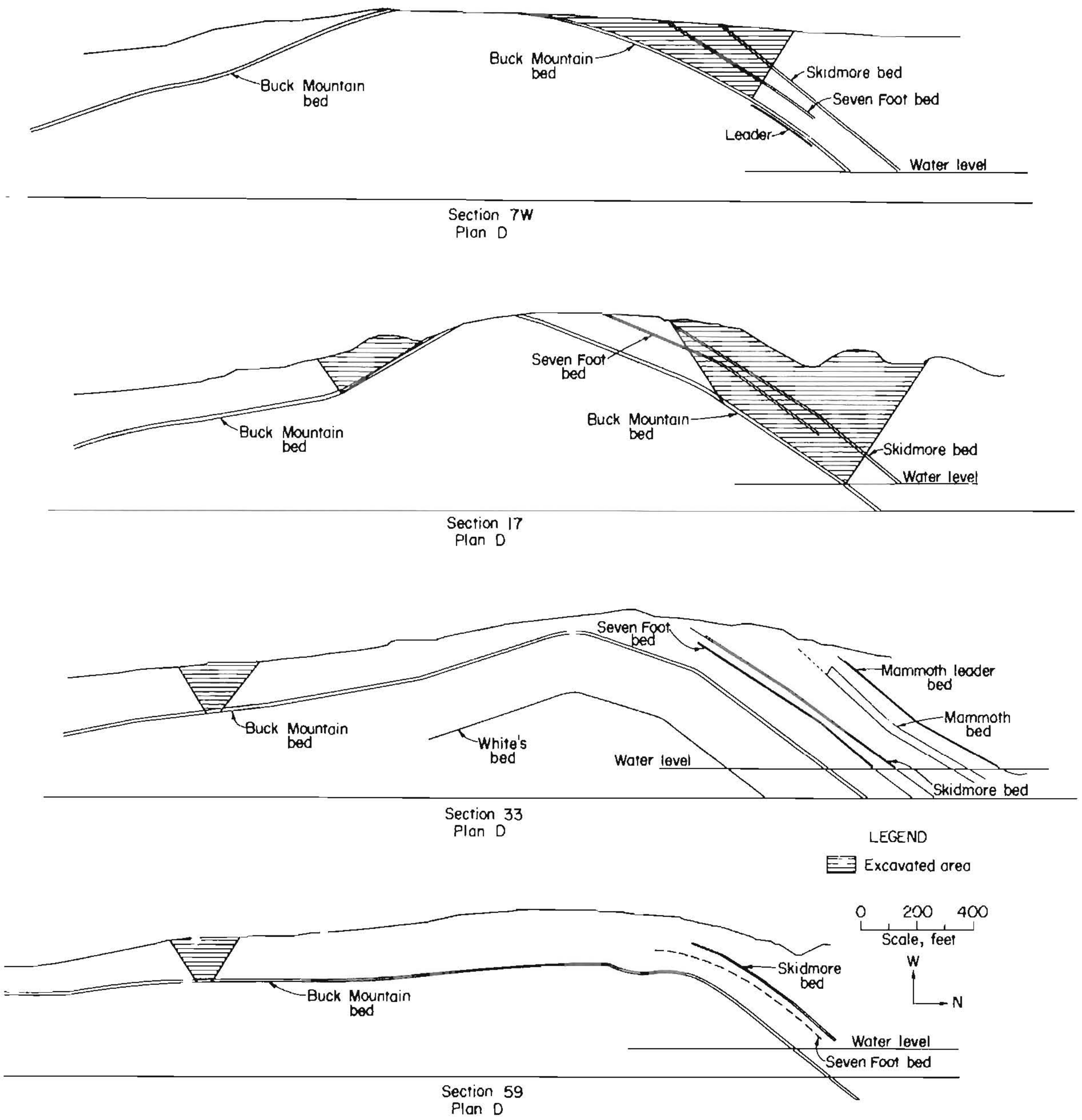

Buck Mountain bed
Buck Mountain bed
Skidmore bed
Seven Foot bed
Leader
Water level
Section 7W
Plan D
Seven Foot bed
Buck Mountain bed
Buck Mountain bed
Skidmore bed
Water level
Section 17
Plan D
Seven Foot bed
Mammoth leader bed
Mammoth bed
Buck Mountain bed
White's bed
Water level
Skidmore bed
Section 33
Plan D
LEGEND
▤ Excavated area
0 200 400
Scale, feet
W
N
Skidmore bed
Buck Mountain bed
Water level
Seven Foot bed
Section 59
Plan D

FIGURE 30. - Cross sections through area of plan D.

As shown in the summary of project work and costs in table 5, of the four excavation plans, only plan C is less costly. The advantages of plan D include the removal of the high-temperature area within the borough limits. Also the use of a cutoff trench on the north dip excavated to water level would destroy fewer homes than the trench in plan C. The isolation trench on the south dip could be made a separate project from the excavation on the north dip. The disadvantages include (1) the condemnation of 112 structures in the town of Centralia, (2) the relocations of State Highway Route 61, (3) the relocation of a natural gas line and surface utility lines, (4) the problems created by isolating 77 acres of underground fire within 1,500 feet of the residential area, (5) the relatively high total project costs ($32 million), (6) a 6-year plan for excavation would require equipment capable of excavating 7,500 cu yd/day and a yearly budget of $5.5 million, and (7) obtaining title to the involved properties could only delay the start of the project, allowing the fire to spread and resulting in higher costs.

Summary

Tables 4 and 5 summarize the pertinent construction and cost factors for the various excavation plans. Table 6 summarizes the advantages and disadvantages of each. Of the four excavation plans considered, plan C is the lowest in cost, but would have the largest impact on the borough (134 homes destroyed). This is primarily due to the north dip isolation trench, which at water level would be 540 feet deep. Excavation of that trench with proper slopes and benches would involve a sizable surface area north of the water table natural barrier. The homes in that area are actually not within the potential hazardous fire area, but would be destroyed during the excavation. Plan D would decrease this impact by moving the location of the north dip isolation trench eastward where there are fewer surface structures, but at an increase in the excavation costs of $10 million, which includes extinguishment of the fire within the borough limits. Plans A and B are not only extremely costly, but would require an extremely large number of workers and machines to accomplish the excavations on a reasonable timetable. Plans C and D are technically feasible in this regard.

TABLE 6. - Advantages and disadvantages of excavation options

Advantages	Disadvantages
	EXCAVATION PLAN A
1. Highest probability of success. 2. Land usable for future development.	1. High cost. 2. Destruction of 109 structures. 3. Relocation of Route 61. 4. Relocation of natural gas line and surface utility lines.
	EXCAVATION PLAN B
1. Cost 50 pct of plan A. 2. Removal of high-temperature zone within the borough.	1. High cost. 2. Destruction of 109 structures. 3. Relocation of Route 61. 4. Relocation of natural gas line and surface utility lines. 5. Isolation of 51 acres of underground fire within 1,500 feet of residential area. 6. Potential hazard of unexcavated area.
	EXCAVATION PLAN C
1. Lower cost.	1. Destruction of 134 structures. 2. Relocation of Route 61. 3. Relocation of natural gas line and surface utility lines. 4. Relocation of sanitary and surface drainage features. 5. Isolation of 151 acres of underground fire within the borough.
	EXCAVATION PLAN D
1. Removal of high-temperature zone within the borough.	1. Destruction of 112 structures. 2. Relocation of Route 61. 3. Relocation of natural gas line and surface utility lines. 4. Isolation of 77 acres of underground fire within 1,500 feet of residential area. 5. Relatively high cost.

FLOODING OPTION

In the history of fire control in the Anthracite Region, flooding has been a successful fire control method in active mines when conditions were favorable. Successful application of the technique to the Centralia fire depends upon supplying sufficient water to all the fire areas long enough to completely cool the elevated temperature zones and would require that the mine water level be raised to an elevation above the known fire levels in the Buck Mountain Seam. Due to heavily caved and steeply pitched areas of the Centralia Mine and the widespread area of the fire, flooding of the entire underground mine fire zone is not considered possible.

Figure 31 shows the mine water flow and the discharge points for the Centralia Mine area. Mine maps indicate that the barrier pillars have been connected by the drainage channels between the Raven Run, Continental, and Centralia Mines to the east and between the Locust Run and Bast Mines to the south (fig. 32). The Centralia and Locust Run-Germantown Mines are thus interconnected.

The water level in the interconnected Locust Run-Germantown section is currently at an elevation of 901 feet with water flow into the Bast Mine and discharge through two surface tunnels (901-foot elevation) at the rate of 2,100 gal/min.

The water level for the Centralia Mine is currently at the 1,000-foot elevation with discharge through a drainage tunnel to the surface (992 ft elevation) at the rate of 2,300 gal/min. The Centralia Mine drainage area discharges approximately 4,300 gal/min into surface streams.

A feasibility study was made to determine the possibility of raising the Centralia Mine water level above the existing 1,000-foot elevation. This would require placing 14 concrete seals at various surface and underground locations: 3 seals in underground rock tunnels; 2 seals at surface portals (tunnels); 3 seals in boreholes to the surface; 3 seals at mine slope portals; 2 seals at mine drift portals; and 1 seal in a strip pit (fig. 33).

Before concrete seals could be installed, it would be necessary to solve the following technical problems:

1. The ability to construct concrete dams in mine tunnels that are inaccessible and located 500 feet below the surface.

2. A method for removing the seals with absolute control of the water released.

3. The construction of a watertight seal in a strip pit.

If these technical problems were resolved, the probable maximum rise in water level that could be attained would be 140 feet (to 1,140-foot elevation). At this elevation, surface drainage would occur from the outcrop of the Buck Mountain Seam along the eastern edge of the Centralia Mine area. A 140-foot rise in the water table would bring the water level just up to the lowest observed depths of the elevated temperature zones. Thus, flooding would not extinguish the fire; at best, it would prevent it from propagating further down the north dip.

In addition to the limited effectiveness of this option, the sealing of the Centralia Mine drainage system could create severe environmental problems (fig. 34), for example--

1. The increased water level could destroy the existing mine barrier pillars and result in surface flooding in the region east of the barrier.

2. New mine water discharge points could be created.

3. Existing surface mine water discharge points could be altered.

4. Nearby strip mine coal reserves could be inundated.

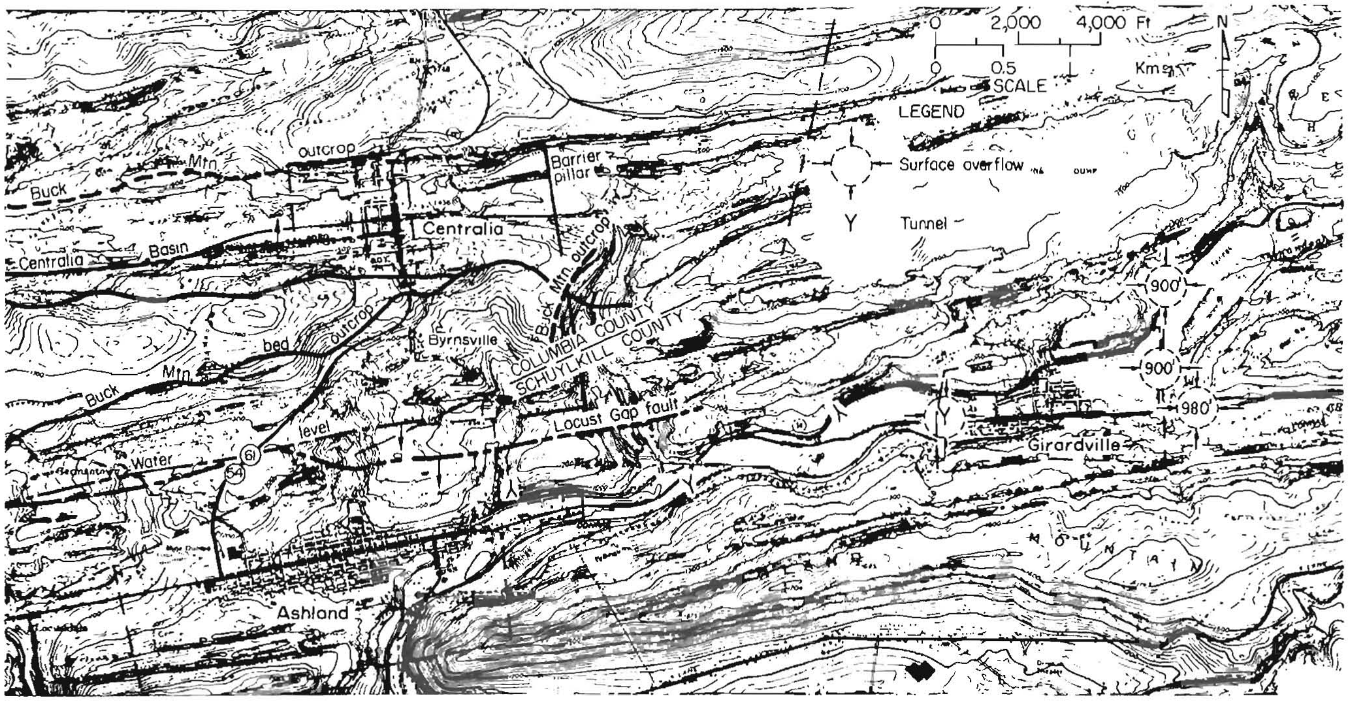

0 2,000 4,000 Ft
0 0.5 Km
SCALE
N
LEGEND
Surface overflow
Tunnel
outcrop
Buck Mtn
Barrier pillar
Centralia
Centralia Basin
Buck Mtn outcrop
Byrnsville
COLUMBIA COUNTY
SCHUYLKILL COUNTY
bed
outcrop
Buck Mtn
level
Water
Locust Gap fault
61
54
900'
900'
980'
Girardville
Ashland
M O U N T A I N

FIGURE 31. - Proposed flooding option for Centralia mine fire with surface drainage points.

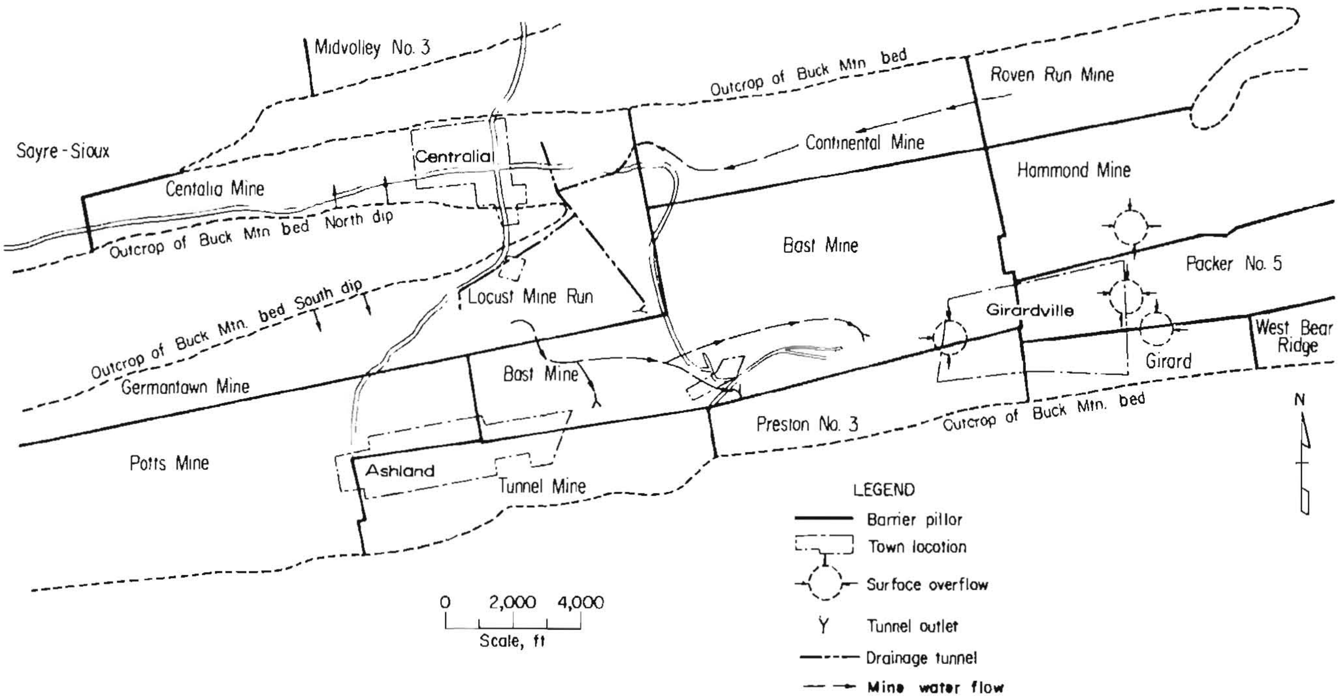
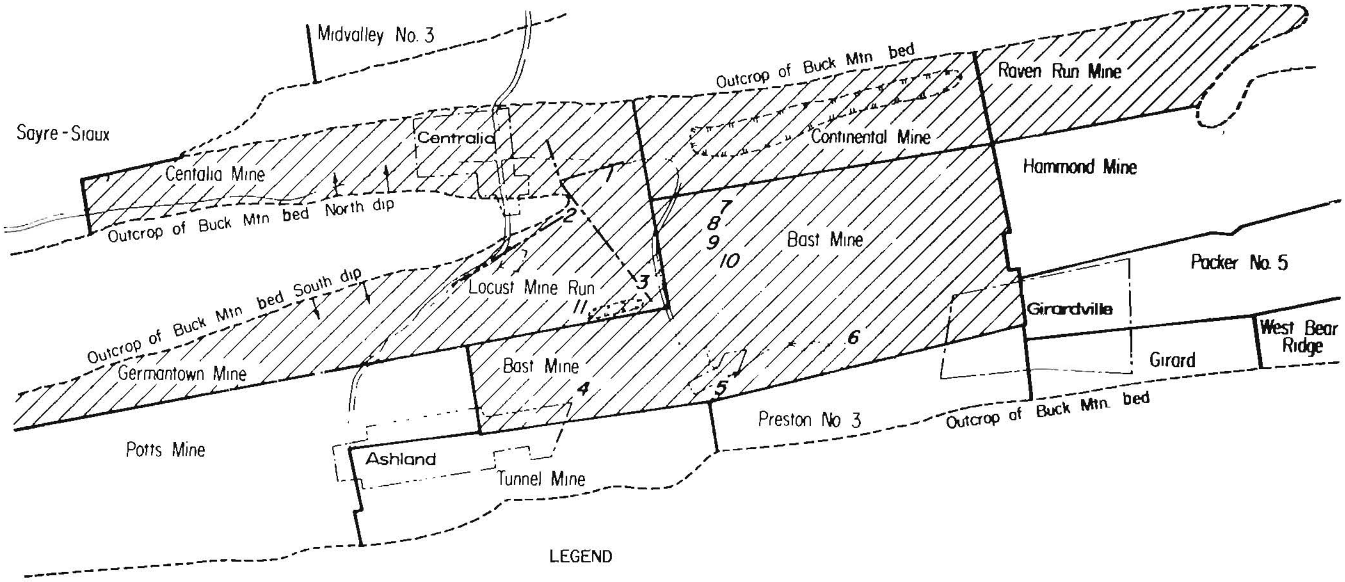

Midvalley No. 3
Outcrop of Buck Mtn bed
Raven Run Mine
Sayre-Sioux
Centralia
Continental Mine
Hammond Mine
Centalia Mine
Outcrop of Buck Mtn bed North dip
Bast Mine
Packer No. 5
Outcrop of Buck Mtn. bed South dip
Locust Mine Run
Girardville
West Bear Ridge
Germantown Mine
Bast Mine
Girard
Preston No. 3
Outcrop of Buck Mtn. bed
N
Potts Mine
Ashland
Tunnel Mine
LEGEND
Barrier pillar
Town location
Surface overflow
Tunnel outlet
Drainage tunnel
Mine water flow
0 2,000 4,000
Scale, ft

FIGURE 32. - Mine map of area of proposed flooding of Centralia mine fire with water flow and drainage points.


Midvalley No. 3
Sayre - Sioux
Centralia
Centalia Mine
Outcrop of Buck Mtn bed North dip
Outcrop of Buck Mtn bed
Continental Mine
Raven Run Mine
Hammond Mine
Bast Mine
Locust Mine Run
Outcrop of Buck Mtn bed South dip
Germantown Mine
Potts Mine
Ashland
Tunnel Mine
Bast Mine
Preston No 3
Outcrop of Buck Mtn bed
Girardville
Packer No. 5
Girard
West Bear Ridge
1
2
3
4
5
6
7
8
9
10
11
LEGEND
Mines affected by proposed flooding of Buck Mtn. coalbed
Barrier pillar
Town location
Drainage tunnel
Strip pit
N
0 2,000 4,000
Scale, ft

PROPOSED LOCATIONS FOR MINE DRAINAGE SEALS

Site No.	Elevation, ft Surface	Elevation, ft Mine	Location
1	1,500	1,000	Tunnel from barrier pillar (Continental Mine)
2	1,500	997	Tunnel to Locust Run Mine
3	1,350	992	Centralia Drainage Tunnel, 800 ft from tunnel
4	901	901	Portal, Bast Mine Tunnel (Ashland)
5	901		3 boreholes at Big Mine Run
6	901	901	Portal, Bast Mine Tunnel, 1 mile west of Girardville
7	1,280	1,280	2 mine slopes, Buck Mtn bed
8	1,287	1,280	Slope, Buck Mtn bed
9	1,150	1,150	Drift, Buck Mtn bed
10	1,140	1,140	Drift, Buck Mtn. bed
11	992		Strip pit

FIGURE 33. - Map of mines with location of dams for proposed flooding of Centralia mine fire.

In summary, the flooding option is not technically feasible, nor would it be particularly effective. This option offers no advantages, and it has the following disadvantages:

1. Flooding would raise the water table only to the base of the fire.

2. Not technically feasible.

3. Could flood downdip surface points.

HYDRAULIC FLUSH OPTION

Hydraulic flushing is one of the basic techniques that recently has been used to control underground anthracite mine fires. Using cased boreholes from the surface, underground fire barriers and seals can be constructed without underground personnel or extensive surface disruption. Hence, it is often one of the techniques considered for mine fire control. Unfortunately, as discussed in a previous section, the success rate for flush barriers and seals is only about 50 pct for Pennsylvania anthracite mines. The use of hydraulic flushing at Centralia in three previous control projects has not been successful. The 1969-70 barrier constructed between Centre and South Streets by gravity flushing was probably effective in retarding propagation of the fire toward the western areas of the borough. However, this barrier has apparently been breached by the penetration of hot fumes, probably through voids and channels in the barrier, which were either never filled or which opened after construction.

The question now is whether a flush tunnel barrier can be constructed at Centralia that will approach 100 pct effectiveness in isolating the fire despite

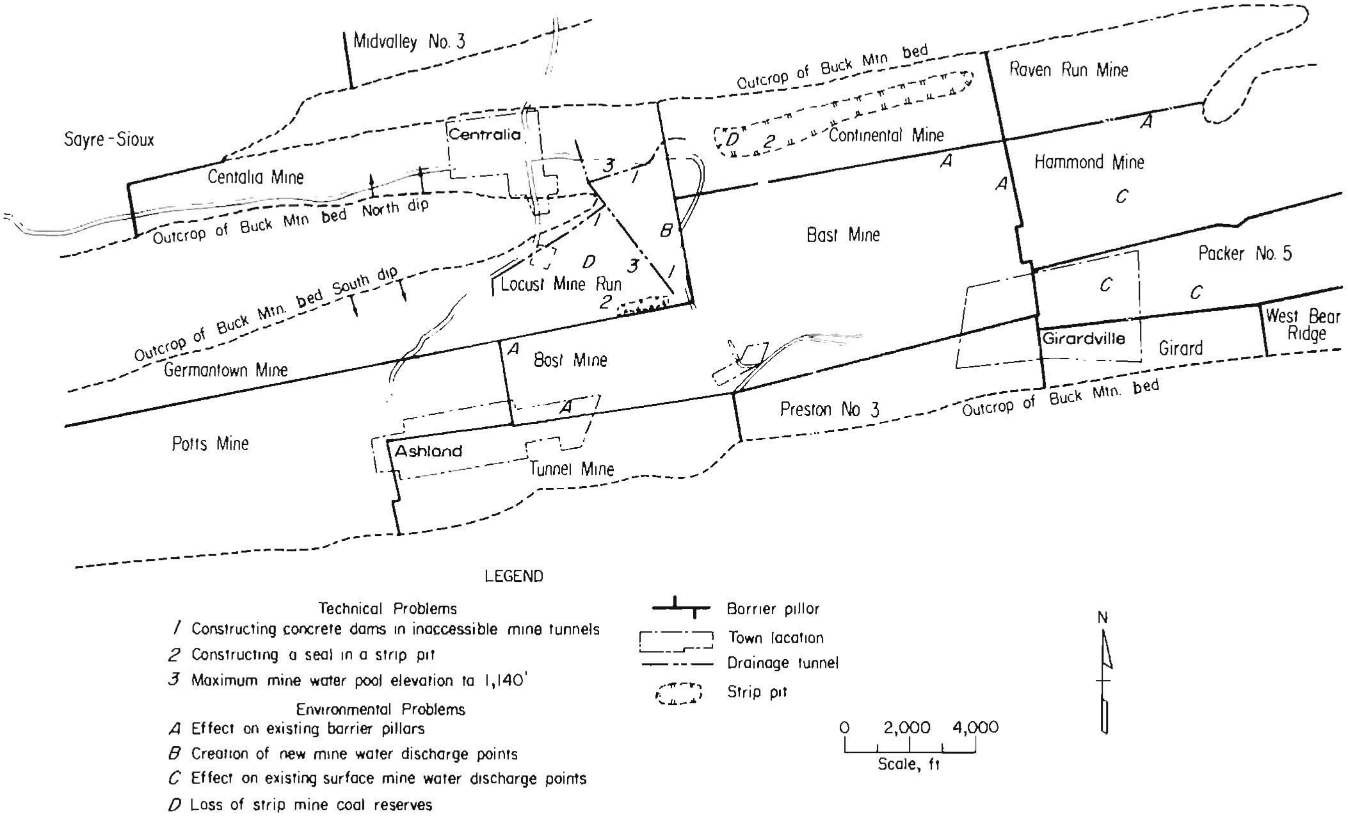

Midvalley No. 3
Sayre-Sioux
Centralia Mine
Centralia
Outcrop of Buck Mtn bed North dip
Outcrop of Buck Mtn. bed South dip
Germantown Mine
Potts Mine
Locust Mine Run
Bast Mine
Bast Mine
Ashland
Tunnel Mine
Outcrop of Buck Mtn bed
Continental Mine
Raven Run Mine
Hammond Mine
Packer No. 5
Girardville
Girard
West Bear Ridge
Preston No 3
Outcrop of Buck Mtn. bed
A
B
C
D
1
2
3
LEGEND
Technical Problems
1 Constructing concrete dams in inaccessible mine tunnels
2 Constructing a seal in a strip pit
3 Maximum mine water pool elevation to 1,140'
Environmental Problems
A Effect on existing barrier pillars
B Creation of new mine water discharge points
C Effect on existing surface mine water discharge points
D Loss of strip mine coal reserves
Barrier pillar
Town location
Drainage tunnel
Strip pit
0 2,000 4,000
Scale, ft
N

FIGURE 34. - Technical and environmental problems associated with proposed flooding of Centralia mine fire.

the inhibiting geological factors discussed earlier (e.g., steep pitch, cavings, etc.). Construction of such a barrier by high-capacity flushing would require detailed monitoring of the underground voids to be flushed, as well as monitoring the effectiveness of the flushing operation during and after barrier construction. The Bureau of Mines has developed borehole TV cameras and sonic dispersion sensors as an intergral part of a remote sealing system. The entire remote sealing system, developed under the Bureau's Coal Mine Health and Safety Program, has twice been successfully used in bituminous coal mines; once as a controlled test and also in an actual mine fire (10).

This remote sealing system (currently assigned to MSHA) is one of the available options that could be used at Centralia. Using the borehole TV camera and sonic dispersion sensor, entries would be examined for their suitability for flush filling before the start of operations. The same equipment would also be used to assess the effectiveness of the flushing process.

The steep pitch (40°) of the Buck Mountain, Skidmore, and Seven Foot Seams, which plunge to the water table (north dip), is an obstacle to constructing an effective flush tunnel barrier. A dam would have to be placed in the entries just above water level (at an approximate depth of 450 feet) to prevent the flush material from being washed downdip into the mine pool. The same remote sealing system might be used for this. A fly ash-cement mixture, fluidized with inert gas, would be injected into the entry under 15 psi pressure until the entire entry cross section is tightly sealed. The formation of seals with this system has not been tested at slopes greater than 15°, and this would have to be investigated before its use at Centralia.

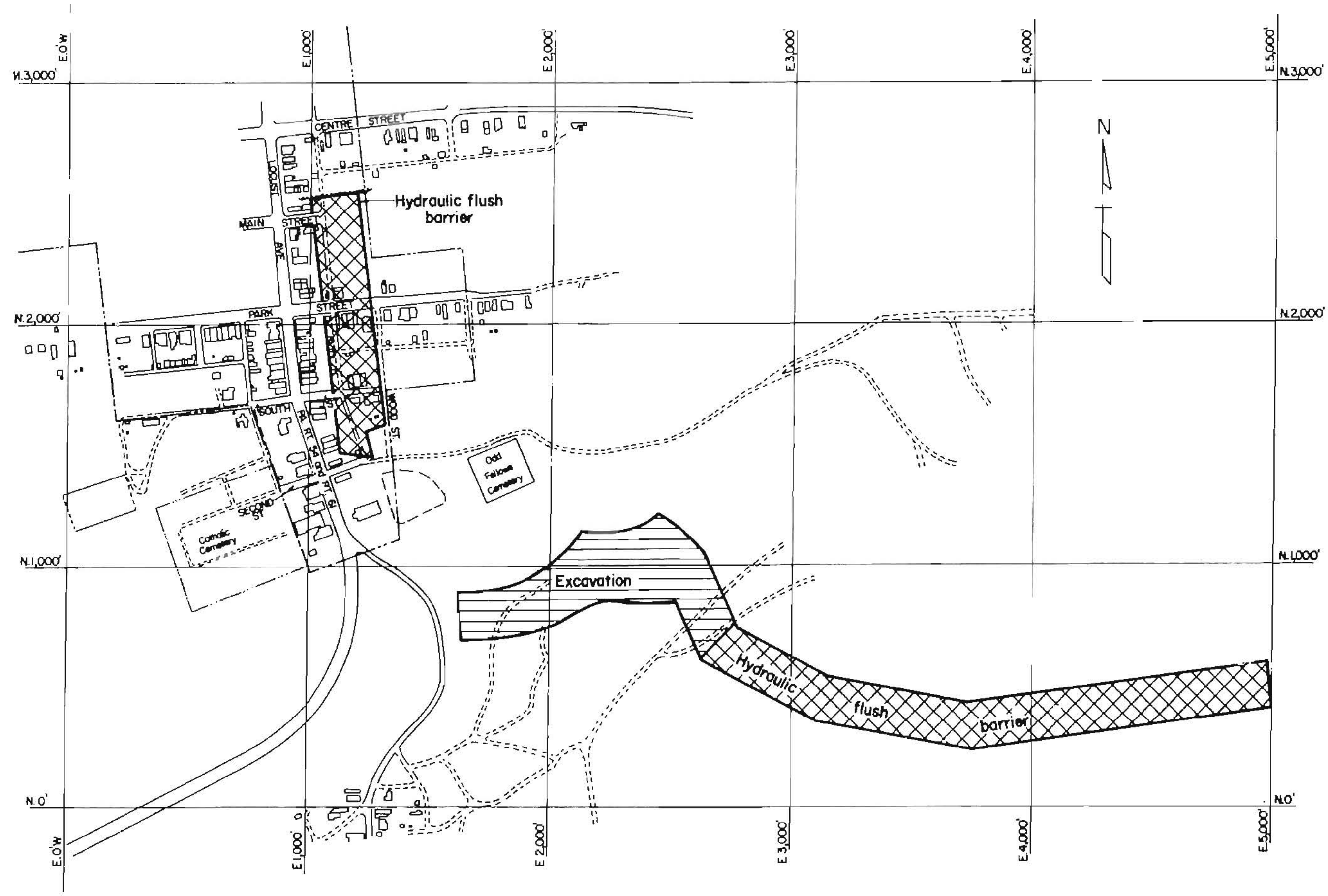
Other methods for constructing dams, such as injection of quick-setting cement slurries, might be considered; however, these, too, would have to be adequately tested. Construction and testing of these dams would be fairly costly. Cost estimates based on previous trials with the remote sealing system run to approximately $100,000 per dam.

Once dams are emplaced in each downdip entry to be filled, flushed material should be injected moving progressively updip from the dam. In highly rubblized areas, pressured flushing will be mandatory to enhance the probability of filling all void areas and channels in the entry and surrounding rock strata. A fly ash-grout or sand-clay-grout mixture capable of setting up permanently must be used.

The length of entry that can be successfully filled from a single borehole would have to be determined by monitoring the field work. However, it is believed that boreholes on 25- to 50-foot centers would be required.

Crosscuts are another obstacle to the formation of an effective flushed tunnel barrier, due to the movement of flushed material out of the entry into the crosscut. Dams could be constructed at each crosscut at great expense, but where the crosscuts are on a horizontal, it would probably be more effective to fill the crosscut. This would be consistent with a tunnel barrier that encompasses several parallel entries. From past experience, four to five parallel entries should be filled in order to form a tight, sealed tunnel barrier of 1,000 feet or more in length, particularly in heavily mined-out areas such as those underlying Centralia.

A combined flush barrier-excavation scheme (fig. 35) for Centralia would isolate the fire between natural barriers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SECOND ST
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Odd Fellows Cemetery
RT 61
Hydraulic flush barrier
Excavation
Hydraulic flush barrier

FIGURE 35. - Proposed hydraulic flushed barrier-excavation option.

(outcrops, water table, and coal pillar) and the constructed flushed tunnel and excavation. In essence, this is similar to previous isolation attempts at Centralia and similar in principle to the excavation plans C and D (figs. 27, 29). The construction procedures constitute the major difference between this flush barrier plan and the previous unsuccessful attempts at Centralia. Each phase of work in this flush option is designed to overcome the obstacles which led to the ineffectiveness of previous fire control projects. However, this leads to a much more expensive flush operation, and the procedures must be considered developmental.

Table 7 is a list of estimated unit costs for a flush tunnel barrier of sand, clay and grout. Table 8 contains the total estimated costs for two fire isolation plans. Plan A is a total flush barrier system without excavation. In essence, the excavated area shown in figure 35 is replaced by continuing the south dip flush tunnel barrier to the western outcrop (fig. 36). The cost for plan A is estimated to be $25.7 million. Plan B is the combined flushing-excavation scheme depicted in figure 35. Its estimated costs are $24.6 million.

In summary, the flush option would be advantageous because the project surface area would remain undisturbed. Its disadvantages are as follows:

1. Previous lack of success. Hydraulic flushing methods to control a mine fire have never been successful in the steeply pitching beds located in the Western Middle Anthracite Field (Centralia area). The proposed construction method is developmental and further testing is required of the techniques to construct underground seals and to contain the injected material.

2. Detailed monitoring. Construction of this type barrier would require detailed monitoring of underground conditions, extending over a long time period (10 years).

3. Shrinkage problems. Techniques must be developed to control shrinkage in the backfill material. Shrinkage-related problems include the seepage of surface drainage into underground workings, humidity of the mine atmosphere, the coalbed pitch, the encroachment of high temperatures, and underground drainage from the hydraulic backfill material.

4. Sealing problems. The problems created in attempting to fill broken strata and seal inaccessible mine workings.

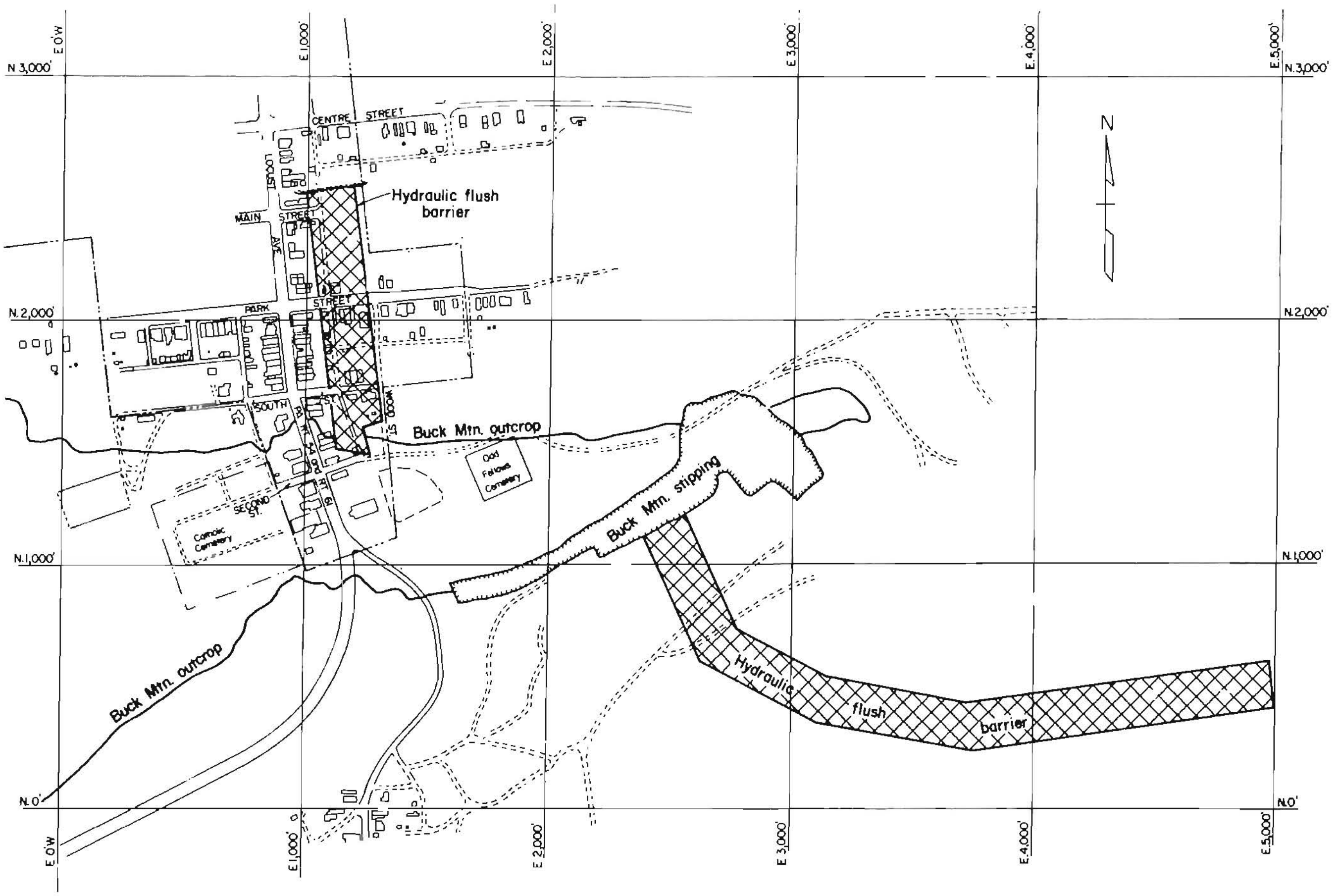
5. High cost. Total project would cost $25 to $26 million.

6. At least 27 structures in the fire zone would have to be destroyed.

7. Approximately 31 structures would be affected by placement of the barrier.

OTHER OPTIONS

In addition to the conventional fire control options already discussed, several unconventional approaches were considered. These methods are considered unconventional either because the effectiveness is unknown, the technical feasibility is doubtful (e.g., water isolation curtain, underground mining of a barrier), or the approach falls outside the realm of technical evaluation (e.g., relocation of the community). Although of doubtful feasibility, these unconventional options are discussed briefly in this section for the sake of completeness.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CENTRE STREET
LOCUST
MAIN STREET
AVE
PARK STREET
SOUTH
WOOD ST
SECOND ST
Catholic Cemetery
Odd Fellows Cemetery
Hydraulic flush barrier
Buck Mtn. outcrop
Buck Mtn. stipping
Hydraulic flush barrier
Buck Mtn. outcrop

FIGURE 36. - Total hydraulic flushed barrier option.

TABLE 7. - Estimated unit costs for flush barrier

Unit Cost Per 1,000 Feet of Entry[1]	
Dam (single)	$100,000
Tunnel flush (sand, clay, grout)	500,000
Drilling, per borehole:[2]	
Western barrier (250 feet, avg. depth)	6,250
Southern barrier (150 feet, avg. depth)	3,750
Monitoring Cost	
Basic equipment	1,000,000
Annual operation and maintenance:	
3 worker-years per year at $35,000 per worker-year	105,000
Maintenance	45,000

---

[1] 10,000 tons per entry (include crosscuts); $50 per ton delivered and injected.

[2] 38 holes/1,000-foot entry; $25 per foot (drill and case).

TABLE 8. · Total estimated costs for flushed barrier option, millions

Total flush barrier

Western Barrier

Seams: 3
Entries: 5 per seam
Length of barrier: 1,000 feet

15 dams	$1.5
Tunnel flush	7.5
Drilling	3.6
Subtotal	12.6

Southern Barrier

Seams: 1
Entries: 5 per seam
Length of barrier: 3,300 feet

No dam	0
Tunnel flush	8.3
Drilling	2.3
Subtotal	10.6
Monitoring--10 years:	
Equipment	1.0
Operation and maintenance	1.5
Subtotal	2.5
Total	25.7

Flush barrier-excavation option (fig. 34)

Western Barrier

Seams: 3
Entries: 5 per seam
Length of barrier: 1,000 feet

15 dams	$1.5
Tunnel flush	7.5
Drilling	3.6
Subtotal	12.6

Southern Barrier

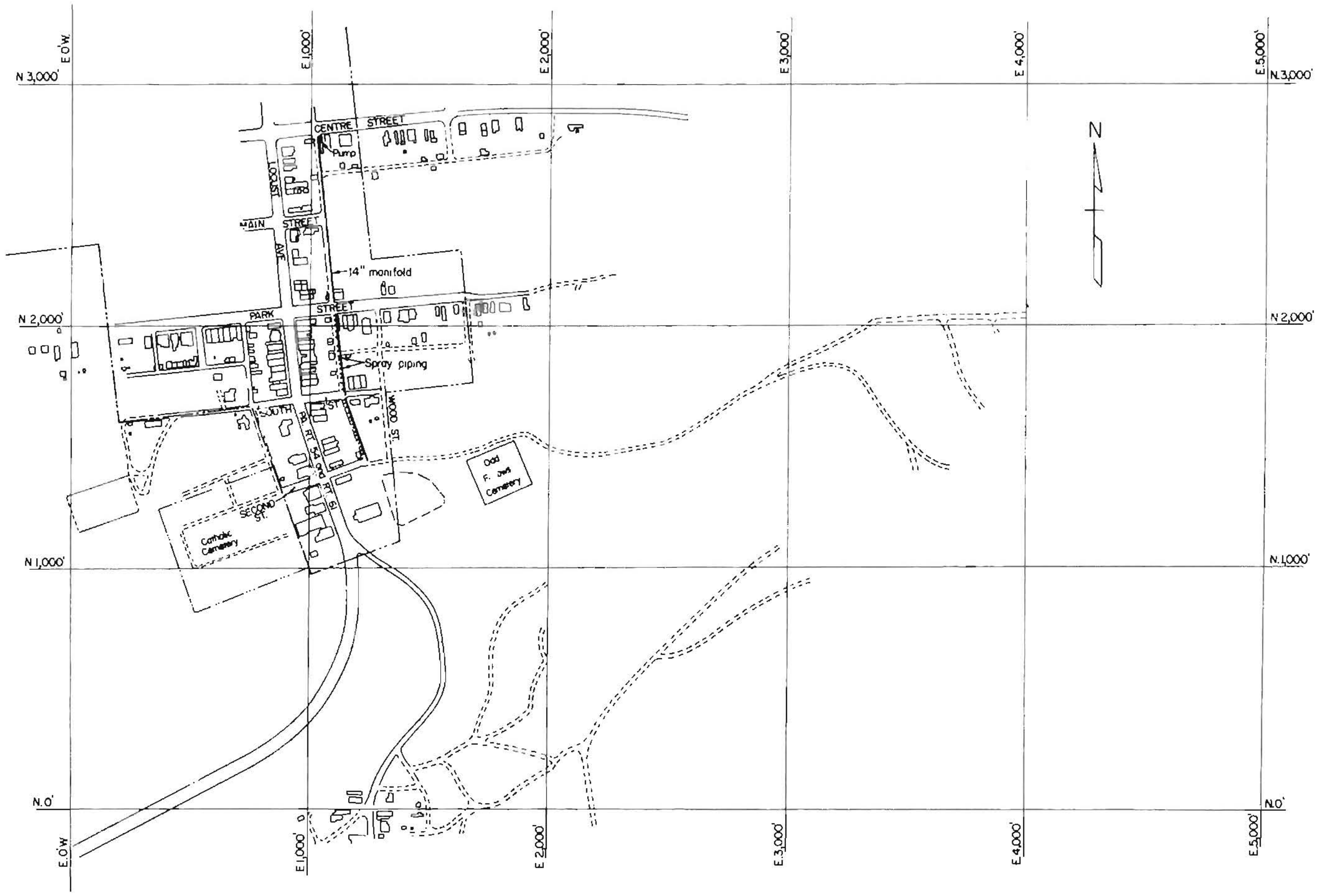
Seams: 1
Entries: 5 per seam
Length of barrier: 2,600 feet

No dam	0
Tunnel flush	6.5
Drilling	1.8
Subtotal	8.3
Southern excavation:	
Length 900 feet, 580,000 cu yd at $2 yd	1.2
Monitoring--10 years:	
Equipment	1.0
Operation and maintenance	1.5
Subtotal	2.5
Total	24.6

Water Curtain Isolation Method

A curtain of continuous underground spraying was considered as a method of containing the Centralia fire. The basic premise is that if a sufficiently large area were kept cold and wet, the fire could be isolated in a particular area; the water would in effect create an incombustible barrier that would also absorb large quantities of heat. The proposed method requires continuously spraying mine water into the three steeply pitched abandoned coalbeds adjacent to the affected area (fig. 37). The water spray system would include a series of 4-inch steel pipes, with high-pressure nozzles (fig. 38), extending from the surface to slightly below the roof of each bed (fig. 39). Preliminary specifications call for spray units on 20-foot centers. A deep well pump would be installed to draw mine water from the water pool approximately 450 feet below the surface. The system would be operated continuously, i.e., 24 hours per day, 7 days per week.

Cost estimates are listed in tables 9-11. The annual operating cost would be approximately $425,000. Assuming that the water curtain would have to be maintained for 20 years to achieve total control of the fire, the total cost would be approximately $9.8 million, which does not include replacing equipment, monitoring, nor the construction of an isolation barrier on the south dip.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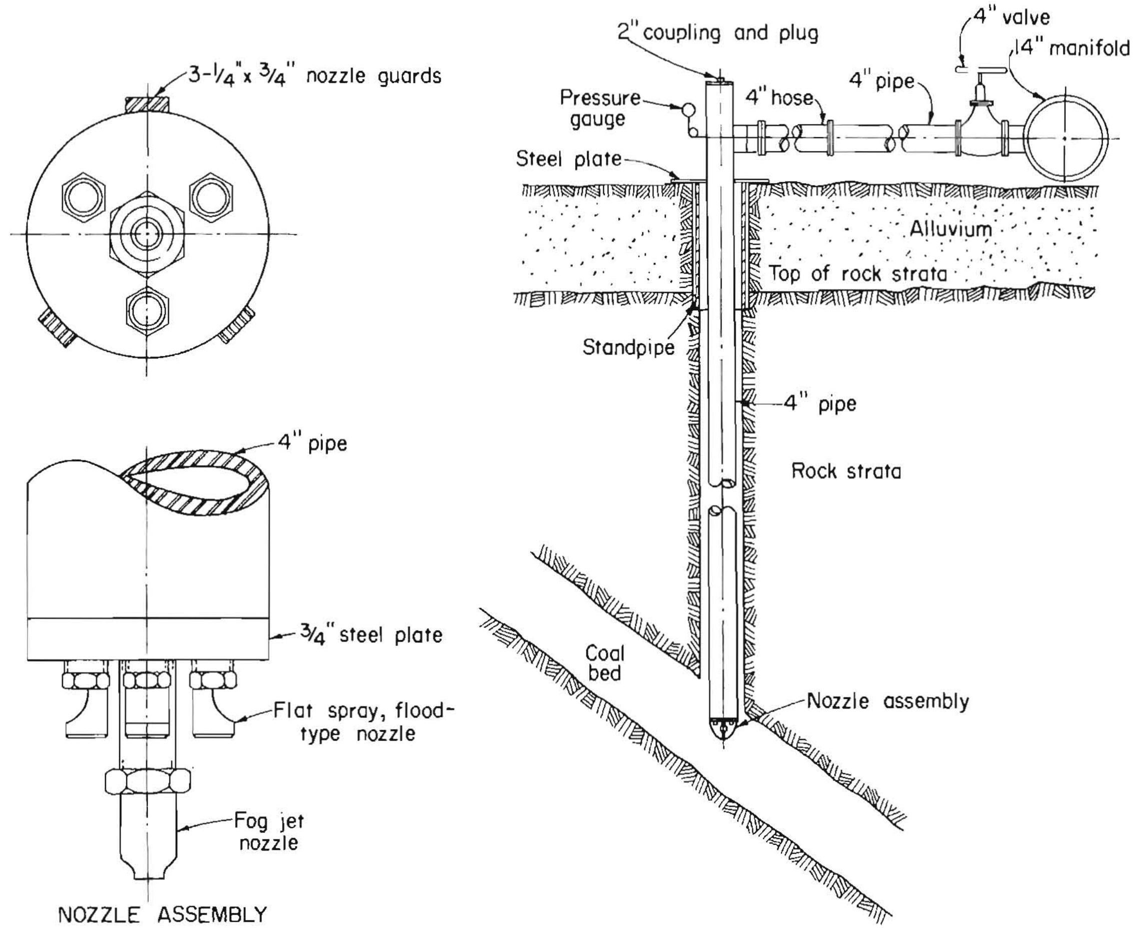
CENTRE STREET
Pump
LOCUST
MAIN STREET
AVE
14" manifold
PARK STREET
Spray piping
SOUTH ST
PA. RT 54 and RT 61
WOOD ST
SECOND ST.
Catholic Cemetery
Odd F. Jws Cemetery
N

FIGURE 37. - Location of proposed water curtain isolation barrier.


3-1/4" x 3/4" nozzle guards
4" pipe
3/4" steel plate
Flat spray, flood-type nozzle
Fog jet nozzle
2" coupling and plug
4" valve
14" manifold
4" pipe
4" hose
Pressure gauge
Steel plate
Alluvium
Top of rock strata
Standpipe
4" pipe
Rock strata
Coal bed
Nozzle assembly

NOZZLE ASSEMBLY

WATER SPRAY SYSTEM

FIGURE 38. - Spray nozzle and assembly for water curtain isolation barrier.

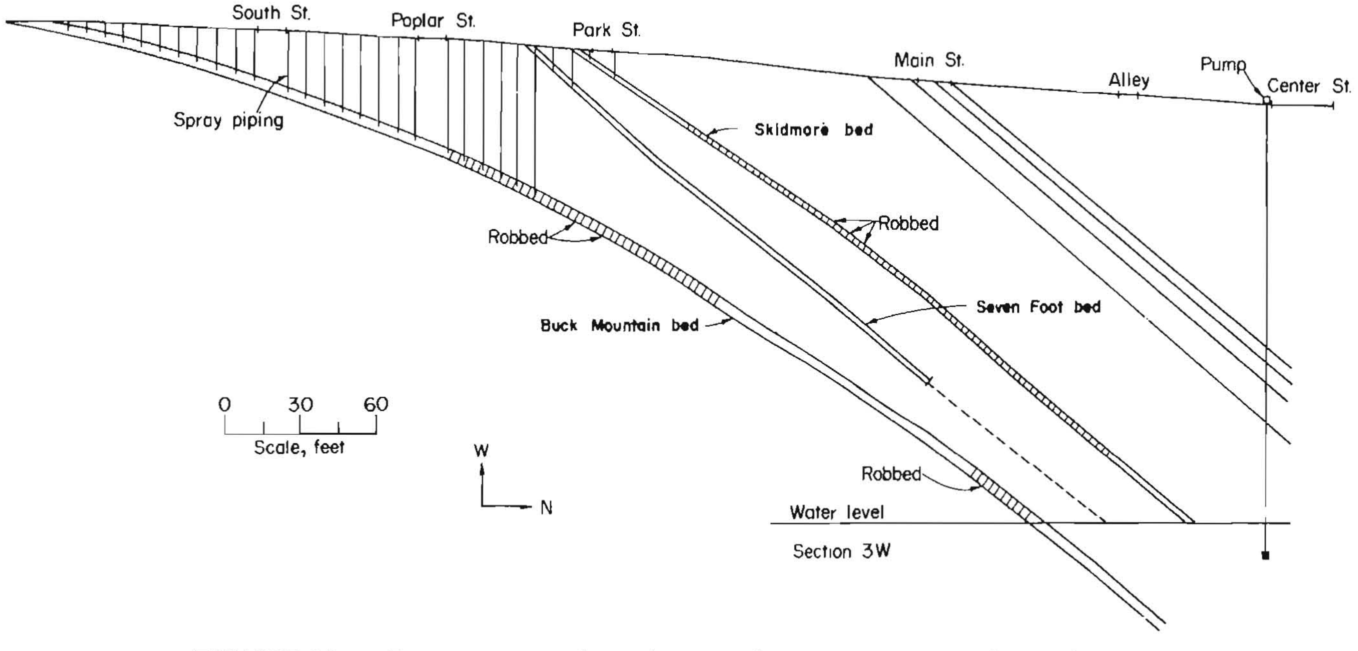

South St.
Poplar St.
Park St.
Main St.
Alley
Pump
Center St.
Spray piping
Skidmore bed
Robbed
Robbed
Seven Foot bed
Buck Mountain bed
0
30
60
Scale, feet
W
N
Robbed
Water level
Section 3W

FIGURE 39. - Cross section through area of water curtain isolation barrier.

TABLE 9. - Capital cost of water curtain isolation barrier, thousands

Equipment	Estimated cost
Deep-well pump, with oil lube, 1,200 HP, including electric starting equipment. (Delivery 36 weeks)	$400
Pump borehole, approximately 450 feet at $600 per foot	270
Pump installation	50
Boreholes for spray piping 150 holes	320
Spray piping installation	200
Miscellaneous	25
Total construction	1,265
Contingency	75
Total	1,340

TABLE 10. · Estimated operating costs of water curtain isolation barrier

	Cost per month
Power	$30,000
Pump operators (3)	5,000
Maintenance	500
Total	35,500

TABLE 11. - Total cost of water curtain option

	Millions
Capital cost	$1.3
Operating cost (continuous operation for 20 years)	8.5
Total[1]	9.8

[1] Does not include cost of monitoring the fire zone for 20 years.

The advantage of this option is the relatively limited surface disruption. The disadvantages are as follows:

1. This method has never been tried, even on a small scale. Therefore, there are no data with which the technical feasibility or the probability of success can even be estimated.

2. Even if the fire were contained by this method, it is possible for cold combustion gases to migrate through the water curtain. Such toxic or explosive gases could cause fume problems or reignition of the fire on the cold side of the water curtain.

3. The effects of the proposed continuous inundation on downdip drainage and surface stability are unknown.

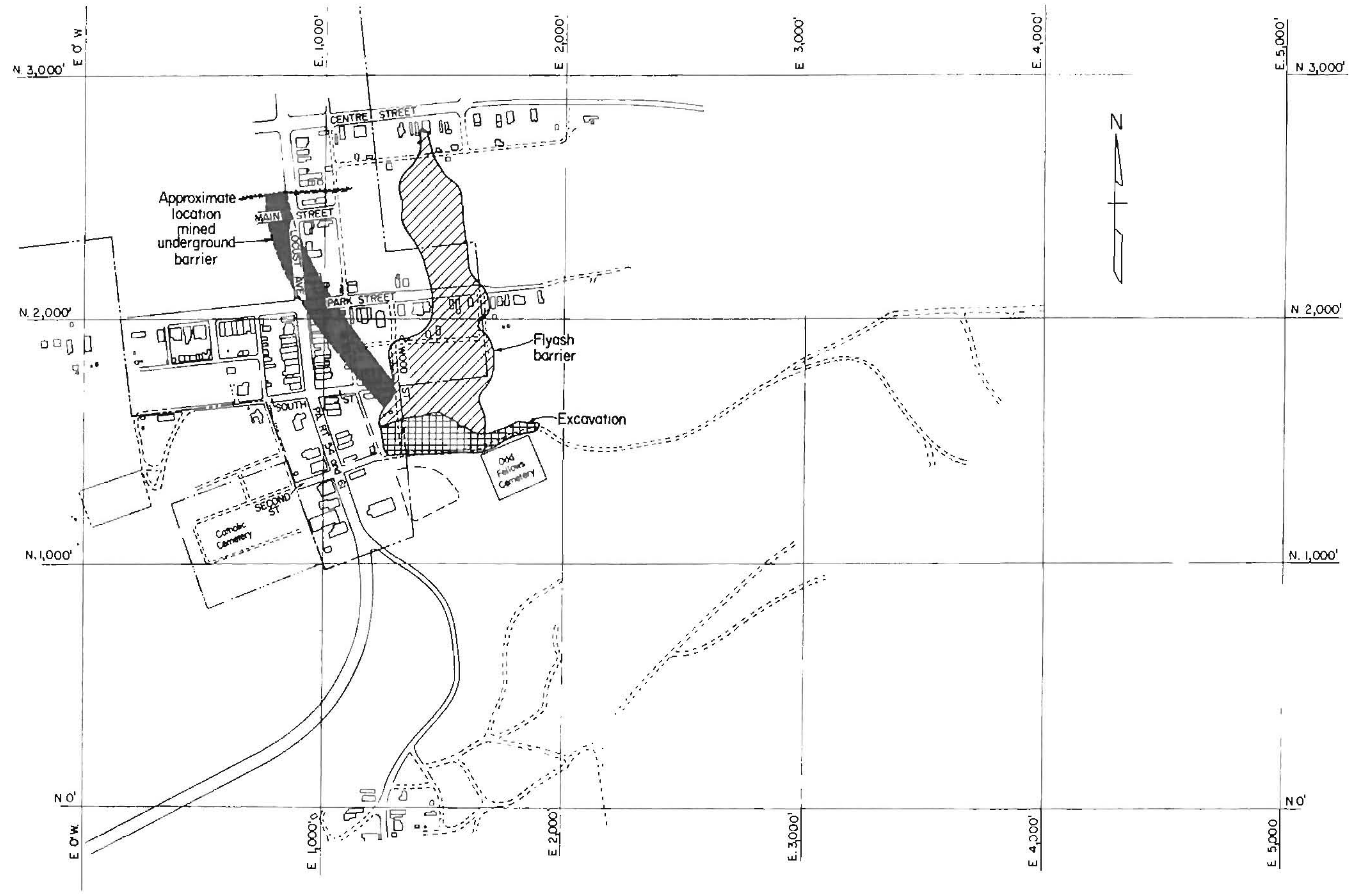
4. At least 40 structures in the fire zone would have to be destroyed.

5. An unknown number of structures would be affected by the drainage.

Underground Mining for Barrier Construction

The possibility of constructing an isolation barrier in the north dip by underground mining techniques as opposed to flushing techniques (fig. 40) was examined. This would combine the effectiveness of the trench barrier with the minimal surface disruption of the flush tunnel barrier.

Using shrinkage stoping mining techniques (4), a slab-shaped area, extending from the bottom of the Buck Mountain Seam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LOCUST AVE
PARK STREET
WOOD ST
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PA RT 54 and 61
SECOND ST
Catholic Cemetery
Odd Fellows Cemetery
Approximate location mined underground barrier
Flyash barrier
Excavation

FIGURE 40. - Location of mined underground barrier.

to the top of the Seven Foot and Skidmore Seams, would be mined out (fig. 41). It would then be backfilled with incombustible material to form a fire barrier about 100 feet wide and almost 1,000 feet long.

The feasibility of doing this in a multiple coalbed area that has been already second- and third-mined by room-and-pillar techniques is highly questionable. Extended roof fracture and collapse would make it extremely hazardous for underground personnel. Adequate roof support and rock removal might be difficult if not impossible to achieve. The hazards of fume circulation from the fire zones would also impose serious constraints. The use of mine rescue teams with air breathing apparatus would probably be required for all underground operations. Approval of mining plans by MSHA would be mandatory, and it is unlikely that sufficient experienced personnel would be available. To establish the feasibility of using a shrinkage stope mining method on the north dip, extensive assessment drilling would be required to determine the condition of each bed, particularly at the north end of the proposed barrier at an elevation of 1,004 feet in the Buck Mountain bed, 1,160 in the Seven Foot, and 1,002 in the Skidmore. Drilling would proceed from 1,004-foot elevation in the Buck Mountain bed up the pitch to the outcrop. Similarly, in the Seven Foot and Skidmore beds, the initial start would be at the 1,160 and 1,002-foot elevations, respectively. The thickness of strata between the beds beginning at the Mammoth is 95 feet to the Skidmore, 50 feet from Skidmore to the Seven Foot, and 75 feet from the Seven Foot to the Buck Mountain bed. Assessment drilling would consist of rotary boreholes to locate voids suitable for drilling large-diameter (40-inch) cased boreholes for both access and ventilation of the particular bed being worked in.

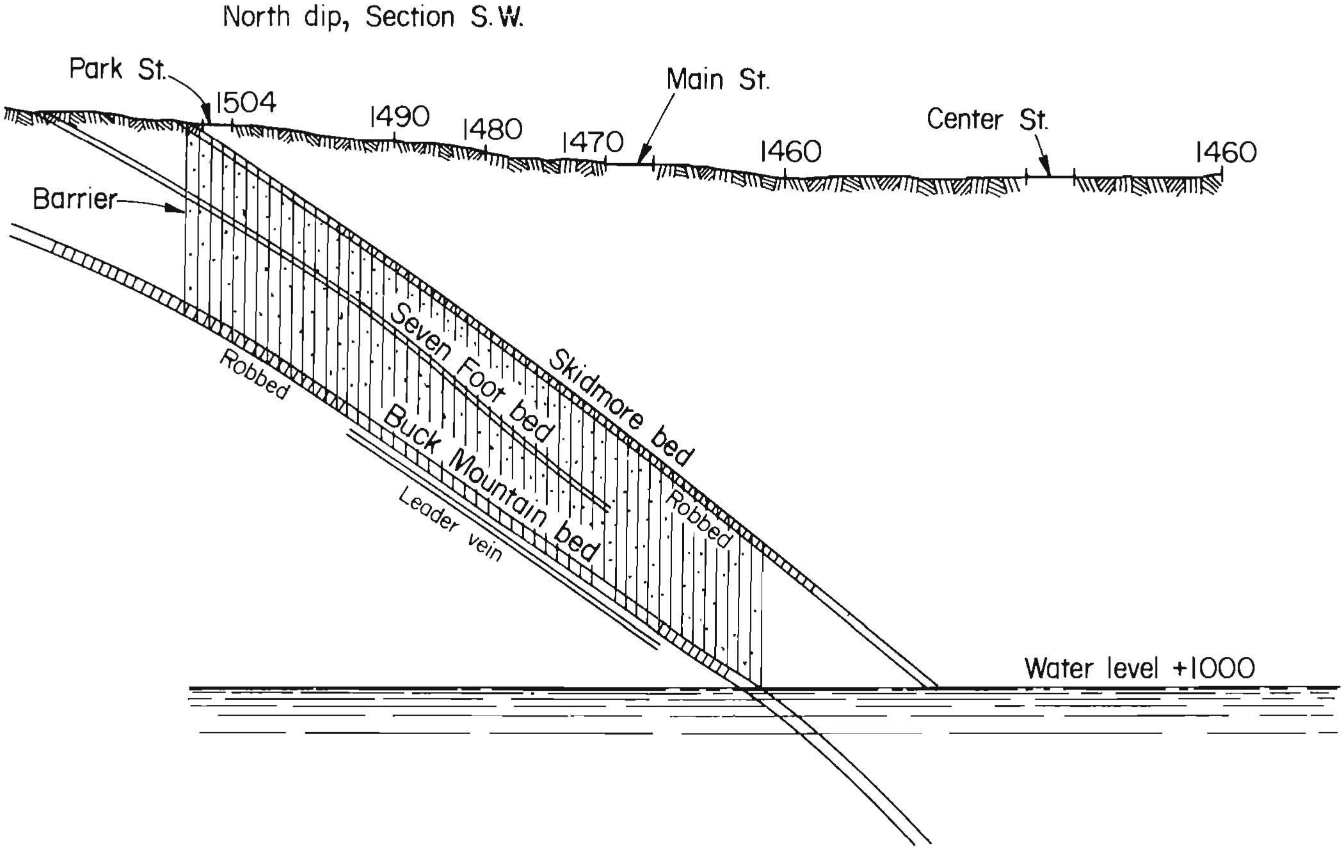

FIGURE 41. - Cross section of mined underground barrier.

The width of a barrier would range from 150 to 200 feet, including three or four chambers on each mining level. This width could be reduced where competent top and bottom rock in a particular bed is encountered.

Access for workers, equipment, and supplies is recommended through a draft opening approximately 1,100 feet west of the initial fly ash barrier, which was reinforced in 1978. The shrinkage stoping method would not be feasible for areas where the overburden is relatively thin. In the vicinity of the Buck Mountain excavation where the cover is approximately 40 feet, excavation from the surface would still be required.

Assuming the method is technically feasible, the estimated costs for the shrinkage-stoping (including drilling, reopening gangways, excavation, and backfilling) would exceed $11 million. This assumes optimum conditions in the underground workings. Deterioration of the tunnel and gangways would escalate the hazard and the cost. To thse costs must be added the cost of constructing an isolation barrier along the south dip.

This method is probably not feasible because, although it reduces surface disruption, it has the following disadvantages:

1. It would require MSHA approval.

2. Workers would be exposed to hazardous conditions in working under heavily fractured roof and in areas where it would be very difficult (if not impossible) to establish ventilation.

3. Underground mining and the isolation barrier would involve high costs.

4. The method is unproven.

5. At least 34 structures in the fire zone would have to be destroyed.

Burnout Control

In recent years, the Bureau of Mines has studied the in situ combustion of coal and is currently developing an alternate approach to the conventional control of active fires in abandoned coal mines (2). This approach involves the controlled acceleration of the fire by air injection so that complete fuel removal is accomplished in a relatively short time compared to a "normal" waste coal burntime of many decades. By developing burn channels in abandoned mine workings (fig. 42), it should be possible to effect a controlled complete burnout of the coal and all other nearby combustibles, such as the carbonaceous rock materials and the pyrites. Unlike all previous underground coal burning systems (e.g., in situ coal gasification), injection of air and removal of combustion products is to be accomplished by exhaust ventilation from the surface.

The advantages, disadvantages, and uncertainties of the burnout control option are listed in table 12. In summary, this approach has a number of advantages:

1. The affected coal mine workings will be at negative pressure relative to ambient; hence, little or no fumes will be emitted to the atmosphere except at the fan exhaust points.

2. Accumulation of all the fumes at fan exhaust points will enable post incineration of the exhaust to insure complete combustion of CO and unburnt soot and hydrocarbons to CO_2 and H_2O. If required, scrubber treatment can also be applied to remove air pollutants such as SO_2 and particulates. Controlled fume removal would also prevent the migration of toxic or explosive gases into other underground areas or homes.

3. Controlled air injection might enable the burn to be carried out under oxidation conditions favorable for SO_2 to react in situ to form solid sulfates, e.g., $CaSO_4$, which would remain in the ground.

4. The heat of combustion of the burning fuel will appear as sensible heat in the exhaust products (perhaps at a temperature as high as 1,800° F). This heat can be recovered onsite for local use (production of steam, hot water, process heat, electricity, etc.).

5. The complete burnout of combustible material (carbonaceous material and pyrites) in a mine will solve once and for all the environmental problems of an active fire. In contrast, fires extinguished by wetting and sealing would leave "wasted" coal with its potential for reignition and acid water formation.

6. Handling of solid materials will be minimal as compared to conventional control techniques such as excavation and flushing.

TABLE 12. - Advantages, disadvantages, and uncertainties of burnout control option

Advantages	Disadvantages	Uncertainties
1. Minimizes surface disruption.	1. Unproven technique.	1. Number of structures destroyed.
2. Eliminates fume problem.	2. Unknown costs.	2. Location and cost of underground containment barriers.
3. Possible heat recovery.		
4. Potential reignition eliminated.		

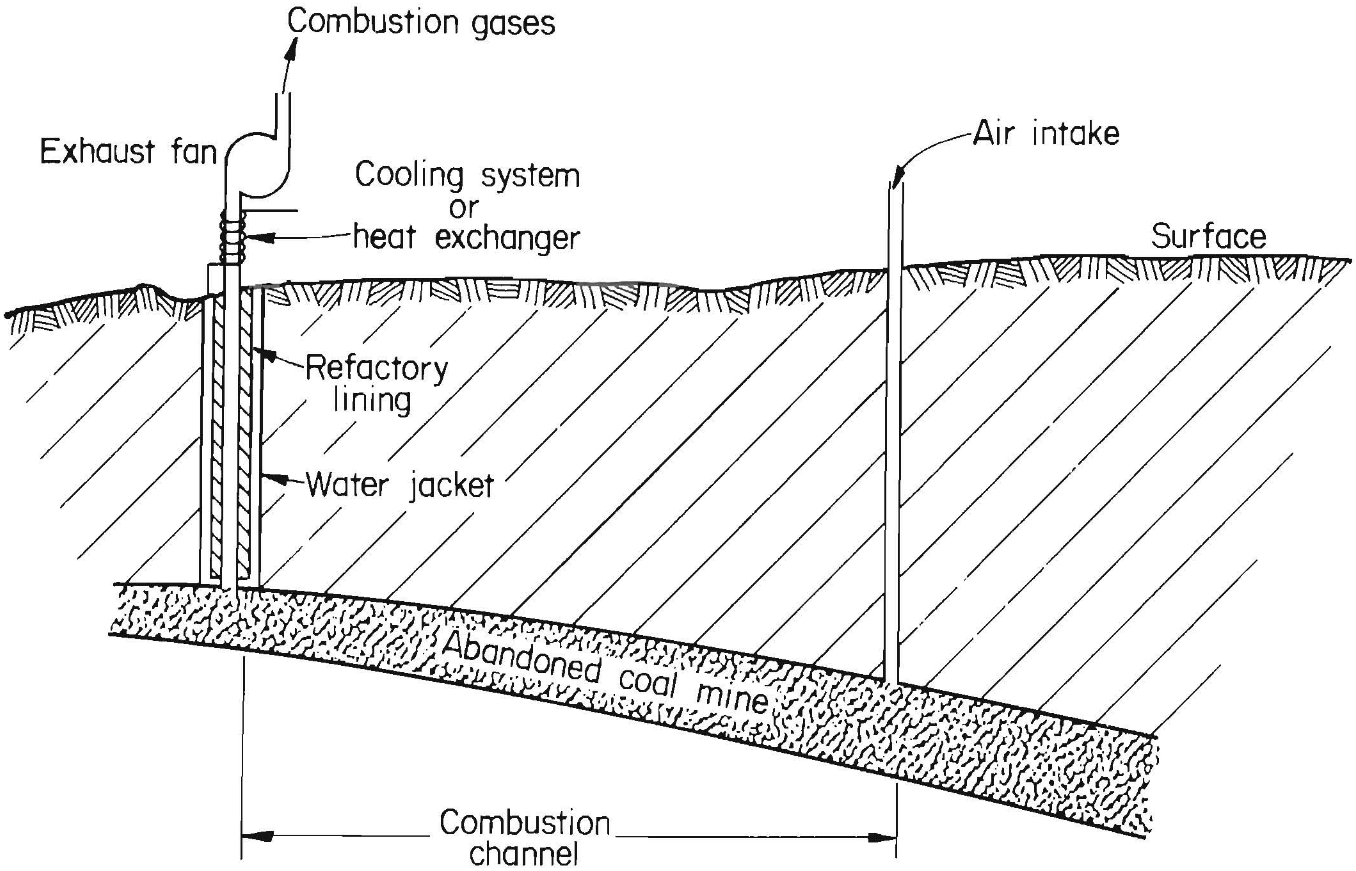
Combustion gases
Exhaust fan
Cooling system or heat exchanger
Air intake
Surface
Refractory lining
Water jacket
Abandoned coal mine
Combustion channel

FIGURE 42. - Schematic diagram of proposed burnout control.

The described advantages of burnout control for abandoned coal mine fires would suggest that the technique is a panacea for environmental and energy problems in the Centralia area. However, it must be realized that this technique is untried; there has been no actual, complete demonstration in an abandoned mine.[11] It is assumed that some type of containment barrier would be required to insure that the fire would not propagate beyond the intended burnout control area. At the present time, the cost and location of such barriers is uncertain. Thus, the above statements are speculative and, although they may be highly reasonable based on past and current work, the burnout control technique must be considered developmental in terms of a potential application to the Centralia fire.

Relocation of Communities

An obvious alternative to all mine fire control efforts is to do nothing and let the fire burn itself out. As applied to Centralia, this option would result in the fire's lasting many years, propagating to the extent of the natural fire barriers. Public health and safety considerations would make it mandatory to relocate all affected residents and businesses. Currently, the natural barriers in the Centralia region consist of the mine water pools just north of the present fire zones, the Locust Gap thrust fault to the south, the large coal pillar and Buck Mountain outcrops to the east, and pinchout of the coal-beds about 2 miles west of the borough. The maximum extent of the fire area is about 1,500 acres, which contain about 310 surface structures. Thus, over one-half of the borough of Centralia and all of the village of Byrnsville could be affected by the fire hazards. Estimating the remaining underground coal reserves to be 16,000 tons per acre, approximately 24 million tons of coal would also be affected.

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[11] The Bureau of Mines recently completed a field trial of the burnout control concept at the site of an abandoned coal mine fire in the Pittsburgh Seam (see BuMines RI 8762 "Calamity Hollow Mine Fire Project, Part I. Development and Construction of the Burnout Ventilation System," 1983). Technology for controlling the underground fire and resulting heat and fumes was successfully demonstrated over a scheduled 4-month period. However, the test program did not extend to complete burnout of the coal-estimated to require a 3-year burn time.

The large number of structures (about 2-1/4 times the number involved in excavation plan D) that might have to be condemned in a "do nothing" operation will undoubtedly have an adverse impact on the remaining community, especially that part of Centralia Borough protected by the mine water pool in the north dip). It can be reasonably expected that the costs would be of the same magnitude as those of most of the conventional control options discussed.

EVALUATION OF FIRE CONTROL OPTIONS

In assessing the available options for controlling the Centralia mine fire, it is necessary to consider not only the technical and economic factors, but also the socioeconomic aspects of a control strategy. Because this fire has burned so long and spread so far, any control method with a good chance of success will by necessity result in a major effort, a major expense, and/or a major impact on the community. As a research organization, the Bureau is concerned primarily with the technical feasibility of these methods. A brief discussion of the socioeconomic factors has been included in order to provide a more complete picture of the problems involved.

TECHNICAL FACTORS

In order to compare the probable effectiveness of the fire control options presented in the previous section, they have been categorized according to the following scheme:

Category 1. Scientifically sound, capable of design and cost estimating according to established engineering principles, and tested successfully in the field. Proven methods would normally fall into this category.

Category 2. Scientifically sound, capable of being designed according to established engineering principles, but never field tested, and without a sound basis for cost estimating. Methods primarily developmental in nature would fall into this category.

Category 3. Scientifically sound, but engineering design shows the method to be prohibitive by reason of cost or other nontechnical factors.

Category 4. Scientifically unsound because implementation would be inadequate, would aggravate the existing problem, or would create other problems. Generally, methods that obviously will not work would fall into this category.

A summary of the categorized options is shown in table 13. Excavation plans B, C, and D have been placed in category 1. The past history and the current state of development of mine fire control for the Pennsylvania anthracite fields indicates that, in general, excavation is the only method with proven success. Unfortunately, excavation methods are costly. Among the four excavation plans considered, plan A (complete excavation of the entire fire zone for $84 million) is placed in category 3 by reason of cost, even though complete excavation (or dig-out and quench) is one of two known ways to extinguish a fire with certainty. The other positive method of extinguishment is flooding, but in the case of the Centralia mine fire, this option must be relegated to category 4 owing to drainage and stratigraphic constraints of the region.

TABLE 13. - Categorized options

Option	Category[1]	Estimated cost, millions
Excavation:		
Plan A.............	3	$84
Plan B.............	1	42
Plan C.............	1	23
Plan D.............	1	33
Flushing:		
Plan A.............	2	26
Plan B.............	2	25
Burnout control......	2	(2)
Underground mining...	3	[3]21
Relocation of community...........	3	(2)
Flooding.............	4	(2)
Water curtain barrier	4	[3]20

[1] 1--Proven method; 2--developmental method; 3--prohibitive; 4--scientifically unsound.

[2] Not estimated.

[3] Includes $10 million for excavation of trench barrier along south dip.

In the past, when excavation was deemed prohibitive, flushing techniques were often used as a relatively rapid, inexpensive alternative. Flushing has been used extensively to control anthracite mine fires, but with limited effectiveness, particularly in the Western Middle Field. Where it was successful, it was also expensive. The "improved" flushing option described in this report is costly ($24 million to $26 million), and its procedures are untried. In describing the flushing option, every attempt was made to address the obstacles to a successful operation, and procedures were defined in the hope of overcoming the obstacles. However, many of these procedures have not been adequately field tested; hence, the flushing option as applied to Centralia is developmental in nature and belongs in category 2. It is interesting to note that the estimated cost of the "improved" flush isolation barrier rivals that of conventional excavation-trench construction.

Another category 2 option is burnout control. This method is under current development by the Bureau, but it has not been completely field tested.

Two fire control options were described that clearly belong to category 3. First is the underground mining of an isolation barrier. The hazards to personnel during implementation of this option are extreme; it is difficult to see how the method could be safely implemented.[12] The second option is essentially a "do nothing" option with relocation of the entire communities of Centralia and Byrnsville. The social impact of moving an entire town probably makes this option prohibitive, independent of any consideration of technical and/or cost factors.

The remaining option, the Water Curtain Isolation Barrier, has been placed in category 4. This option has questionable feasibility with regard to ever being able to accomplish the goal of maintaining a uniform spray throughout the entire volume of several entries extending 1,000 feet in length. Also, a water spray curtain would do little to prevent the passage of toxic and/or explosive combustion gases from the fire areas.

Based on the technical factors, the most favorable option is excavation plan D, assuming the current fire assessment is valid. Implementation of this plan would remove all material from the fire zones within the borough, but at less cost than that for plan B, and with less disruption of utilities and roads. Excavation plan C, while less costly than either excavation plan B or D, leaves part of the isolated fire zone within the borough limits. Also, excavation plan C would result in destruction of a number of homes not endangered by the fire. Finally, plan D is a more workable excavation than plans B and D in terms of engineering constructions and time scheduling.

No engineering solutions to the fire control problem at Centralia were identified other than the excavation isolation options, which have a proven degree of success. Yet implementation of an excavation option would require the destruction of approximately one-third of the affected homes. It is also clear that the cost of this engineering solution will lie between $23 and $42 million. This cost and the residence destruction are major considerations in the selection of a control method.

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[12] This conclusion was confirmed by personal communications with D. DeHaven, the Assistant District Manager of MSHA District 1, Wilkes-Barre, PA.

SOCIOECONOMIC FACTORS

In evaluating the available fire control options, it is evident that there are nontechnical factors involved. Even in the technical classification used to categorize the available options, nontechnical factors were part of the criteria used in classifying an option as prohibitive. For example, the community relocation option was placed in category 3 because of its social impact rather than its cost or general feasibility.

The nontechnical aspects of the proposed fire control options were studied in detail by a consulting firm, which has prepared a comprehensive socioeconomic impact analysis of the Centralia mine fire for the Office of Surface Mining (17). Although the Bureau of Mines is concerned primarily with the technical aspects of controlling the mine fire, these socioeconomic factors should be considered in the overall evaluation of the options. In order to present a complete picture of the situation at Centralia, the socioeconomic factors must be considered along with the technical factors. A detailed discussion is outside the scope of this report; however, it is apparent from the socioeconomic study that the proven methods that have the greatest potential for successfully controlling the fire also would have significantly adverse effects on Centralia. In contrast, control methods such as flushing or burnout control, which would have a lesser socioeconomic impact, are not rated as highly from a technical viewpoint because they are either under development or of doubtful feasibility under the given geological conditions. In summary, there is no simple solution for the Centralia mine fire for the communities involved.

SUMMARY

The Centralia mine fire provides one example of many of the difficulties and uncertainties encountered in controlling underground mine fires in the Anthracite Region. For 21 years the fire has continued to spread despite repeated fire control projects.

Conditions that have contributed to the difficulties in extinguishing such anthracite mine fires are related to the geology of the region, the history of previous mining, and the nature of the coal itself. In the Western Middle Anthracite Field, the steep dip of the coalbeds, the fragmented and inhomogeneous gob area, subsidence fractures extending to the surface, and the presence of underground drainage tunnels have provided an environment conducive to the propagation of an underground fire. Oxygen is supplied to the fire through subsidence fractures and circulated underground through the rubblized gob material and underground passageways. The anthracite has a low heat conductivity, resulting in heat retention. A process of "conditioning" or drying of the coal will result after prolonged heating at temperatures as low as 200° F. When oxygen is supplied to a dormant area that has been conditioned, spontaneous combustion may occur, resulting in spread of the fire. This is especially problematic if natural ventilation transfers heat and oxygen through a fire barrier, resulting in the spread of the fire beyond a supposedly sealed area. Also, the combustion of anthracite can produce relatively large quantities of hydrogen, which may migrate through a barrier and then may explode, again causing the outbreak of fire on the cold side of the barrier.

Because of the particular conditions present in the Anthracite Region, control methods that have been widely and successfully applied elsewhere are often ineffective. An evaluation of past fire control experience in the region indicates that excavation is the most successful of the approaches tried.

Flushing was successful in only about half the attempts, probably because of difficulty in completely filling mine voids in the steeply pitching beds. Surface sealing was generally ineffective because the highly faulted strata and subsidence due to mining make it virtually impossible to maintain a tight seal. Flooding has been effective only in active mines where the fire is totally below the level of the water table. Methods such as flushing and trenching may result in the spreading of the fire by altering air and fume circulation underground, resulting in spontaneous combustion in another area.

After consideration of the particular constraints posed by this area, typical propagation characteristics of anthracite fires, and the effectiveness of past fire control efforts, possible fire control plans were formulated for Centralia. These approaches included various excavation approaches, with and without isolation trenches, flushing, burnout control, underground mining, relocation of the community, flooding, and water curtain barriers.

By studying the fire control plans formulated, it was possible to evaluate anticipated effectiveness and relative costs in a real situation. When these options were categorized according to whether they are (1) proven, (2) developmental, (3) prohibitive, for reasons of high cost or other nontechnical factors, or (4) scientifically unsound, only excavation plans B, C, and D fell withn the proven category. The two flushing plans are considered developmental because the seal construction methods are refinements designed to overcome the geological constraints of the region and are as yet untried. Similarly, burnout control has not been adequately field tested. The methods that were categorized as prohibitive are (1) underground mining, because of the hazards to which the miners would be exposed, (2) relocation of the community, because of the considerable socioeconomic ramifications to the community, and (3) excavation plan A, because of the high cost. The final options, flooding and a water curtain isolation barrier were considered to be scientifically unsound because there is little chance of their success under the given conditions.

In 1980 the Centralia mine fire reached major proportions, and if allowed to burn to its natural limits, an area of 1,500 acres and approximately 320 structures in Centralia and Byrnsville would be affected. With a fire of this size, it is recognized that the cost of bringing the fire under control will be relatively high. Similarly, the effect on the financial stability, employment, and social life of the town will be relatively great.

Of the plans evaluated in 1980, the most advantageous from a technical viewpoint is excavation plan D, which calls for total excavation of the high-temperature area on the north dip of the Buck Mountain Coalbed supplemented by a cutoff trench and an isolation trench on the south dip. This is a proven method that will remove the material in the high-temperature area within the borough, leaving an isolated fire zone away from residential areas.

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APPENDIX A.--ASSESSMENT OF THE EXTENT OF AN UNDERGROUND FIRE

In any fire control project, whatever abatement measures are to be used, the first step is to determine the extent of the fire. This includes both the areal extent and depth of the affected underground coal mine working, which together determine the magnitude and location of the fire control project. To locate a fire in an inactive mine, a series of boreholes are drilled from the surface to mine voids to measure temperatures and sample the mine atmosphere. From these, the nature of the strata and conditions of the mine are determined. Generally, boreholes are drilled into areas most likely to contain voids, since holes in solid coal can yield misleading temperature data due to low heat conductivity of the solid.

Normal underground temperature is approximately 55° to 60° F. Temperatures slightly above this may indicate that a fire exists in the vicinity (_6_, _9_). These temperatures can range from 80° to 212° F as measured at various distances from a fire because of the relatively wide vaporization zone. Using the borehole data collected, various approaches have been used by the Bureau to define the fire zones as described below.

ELEVATED-TEMPERATURE MAPS

Elevated-temperature maps are a visual representation of areas of like temperature, as constructed by plotting borehole temperature data on surface (fig. A-1) and mine maps (fig. A-2). In the case of Centralia, these data were collected from 1,800 boreholes (fig. A-3), which had been drilled into 3 coalbeds over a period of 14 years. The boundaries for the temperature zones were based on the most recent data, while the interior temperatures and general shape of the zones are interpreted from all the temperatures recorded for the zone and from the local geometry of the coal seam in which the fire is located (i.e., location of entries, tunnels, pillars, pitch of seam, etc.). No attempt was made to extrapolate the elevated temperatures beyond the immediate area of the borehole locations. Extrapolations were made only for bounding the zone.

In using a map of this sort, it is important to recognize that areas of the map that are not within a bounded area do not necessarily represent cold areas, but regions for which data are not available. Thus, the temperature maps do not accurately define the bold boundary that encloses the entire fire area, and it cannot be assumed that the area surrounding a particular temperature area represents a cold-temperature region. Also, if a borehole penetrates more than one coal seam, only the temperature recorded in the lowest coalbed is considered valid since ventilation updrafts from the lowest borehole depth affect the temperature readings taken higher up.

Despite the limitations of the temperature maps, they are useful in establishing the general area and depth of the fire and the direction in which it is progressing. They are also an important tool in determining whether or not a fire control barrier has been breached by fumes.

COMPUTED ISOTHERMAL CONTOURS

Like the elevated-temperature maps, computed isothermal contour maps are a means of converting borehole temperature data into a visual representation of areas of similar temperature. In this case, instead of simply plotting the data points, the information was analyzed using a computerized map contouring program to extrapolate between randomly spaced data points and generate isothermal lines over the surface of the fire area. Using computer analysis, any quantitative parameter that has a spatial dependence can be used to generate a numerical surface that can be contoured. Contours of a numerical surface are actually a series of interpolations that make it possible in the case of temperature data to approximate temperatures for areas removed from the location of the boreholes.

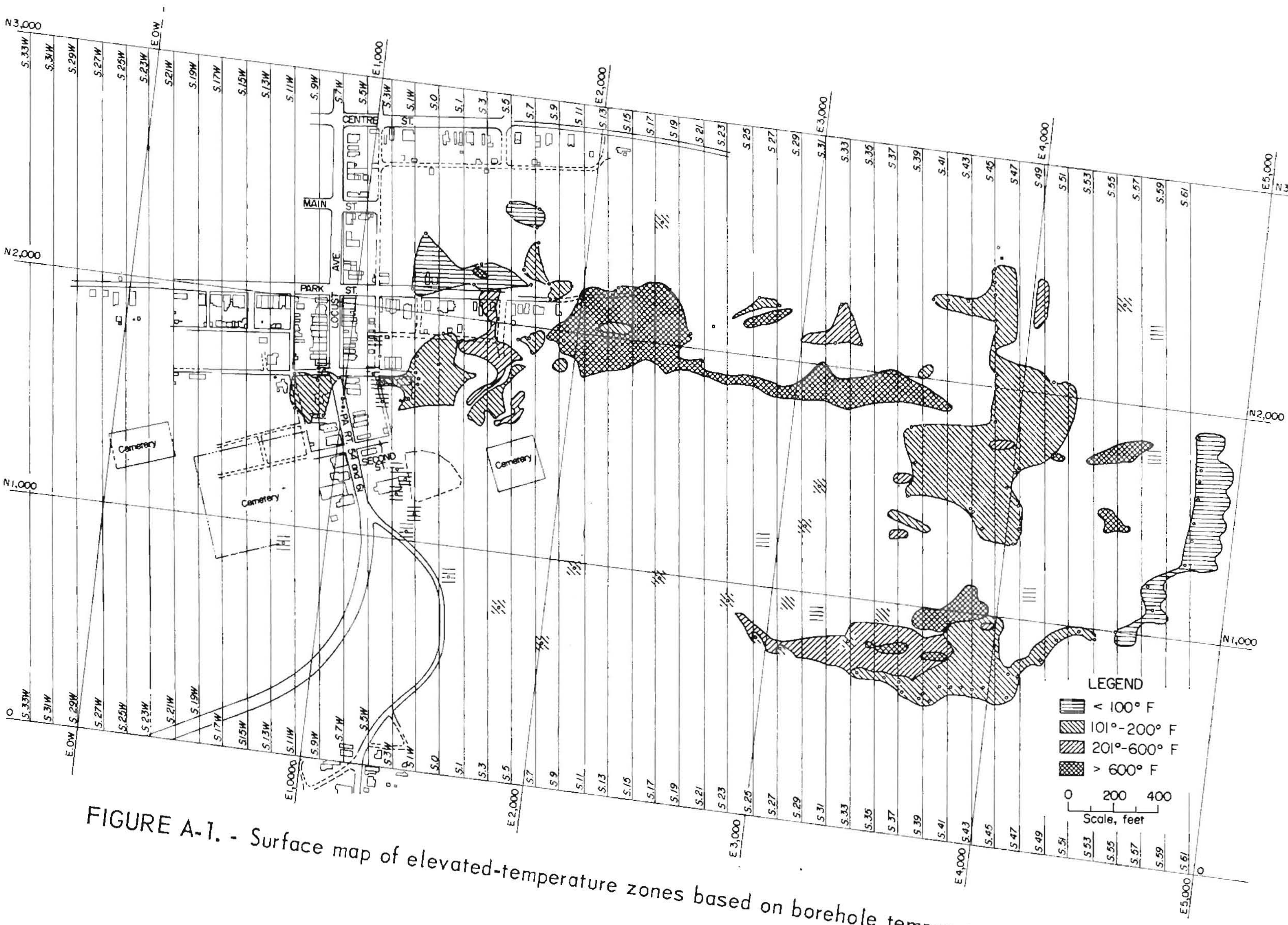

LEGEND
< 100° F
101°-200° F
201°-600° F
> 600° F
0 200 400
Scale, feet
N3,000
N2,000
N1,000
0
E 0W
E1,000
E2,000
E3,000
E4,000
E5,000
MAIN
AVE
PARK
ST
LOCUST
CENTRE
ST.
SECOND
ST.
PA. RT. 54 and 61
Cemetery
Cemetery
Cemetery
S.33W
S.31W
S.29W
S.27W
S.25W
S.23W
S.21W
S.19W
S.17W
S.15W
S.13W
S.11W
S.9W
S.7W
S.5W
S.3W
S.1W
S.0
S.1
S.3
S.5
S.7
S.9
S.11
S.13
S.15
S.17
S.19
S.21
S.23
S.25
S.27
S.29
S.31
S.33
S.35
S.37
S.39
S.41
S.43
S.45
S.47
S.49
S.51
S.53
S.55
S.57
S.59
S.61

FIGURE A-1. - Surface map of elevated-temperature zones based on borehole temperature data.

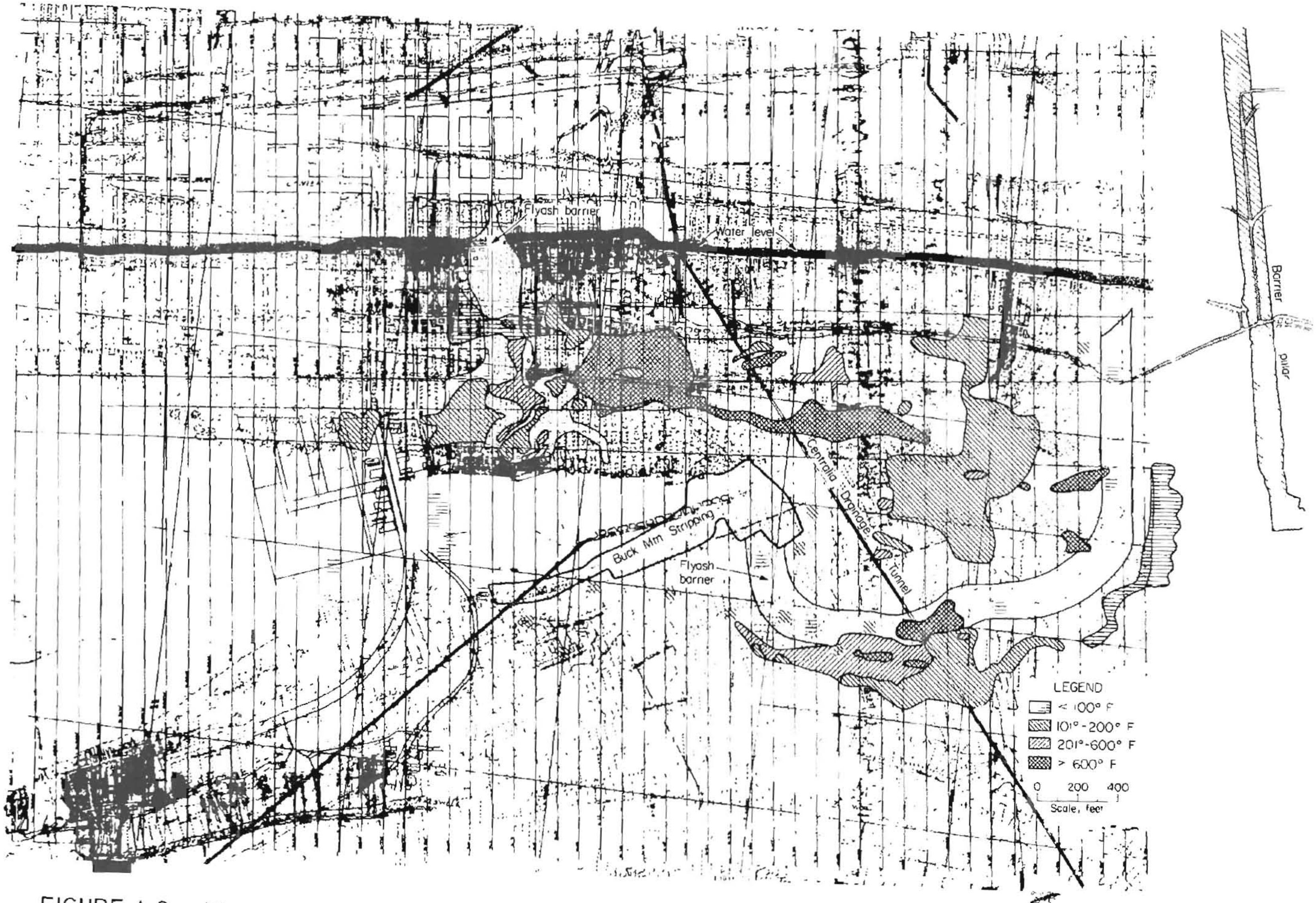

Flyash barrier
Water level
Barrier pillar
Centralia Drainage Tunnel
Buck Mtn Stripping
Flyash barrier
LEGEND
< 100° F
101°-200° F
201°-600° F
> 600° F
0 200 400
Scale, feet

FIGURE A-2. - Mine map of the Buck Mountain Coalbed in the area of the Centralia mine fire, showing elevated temperature zones.

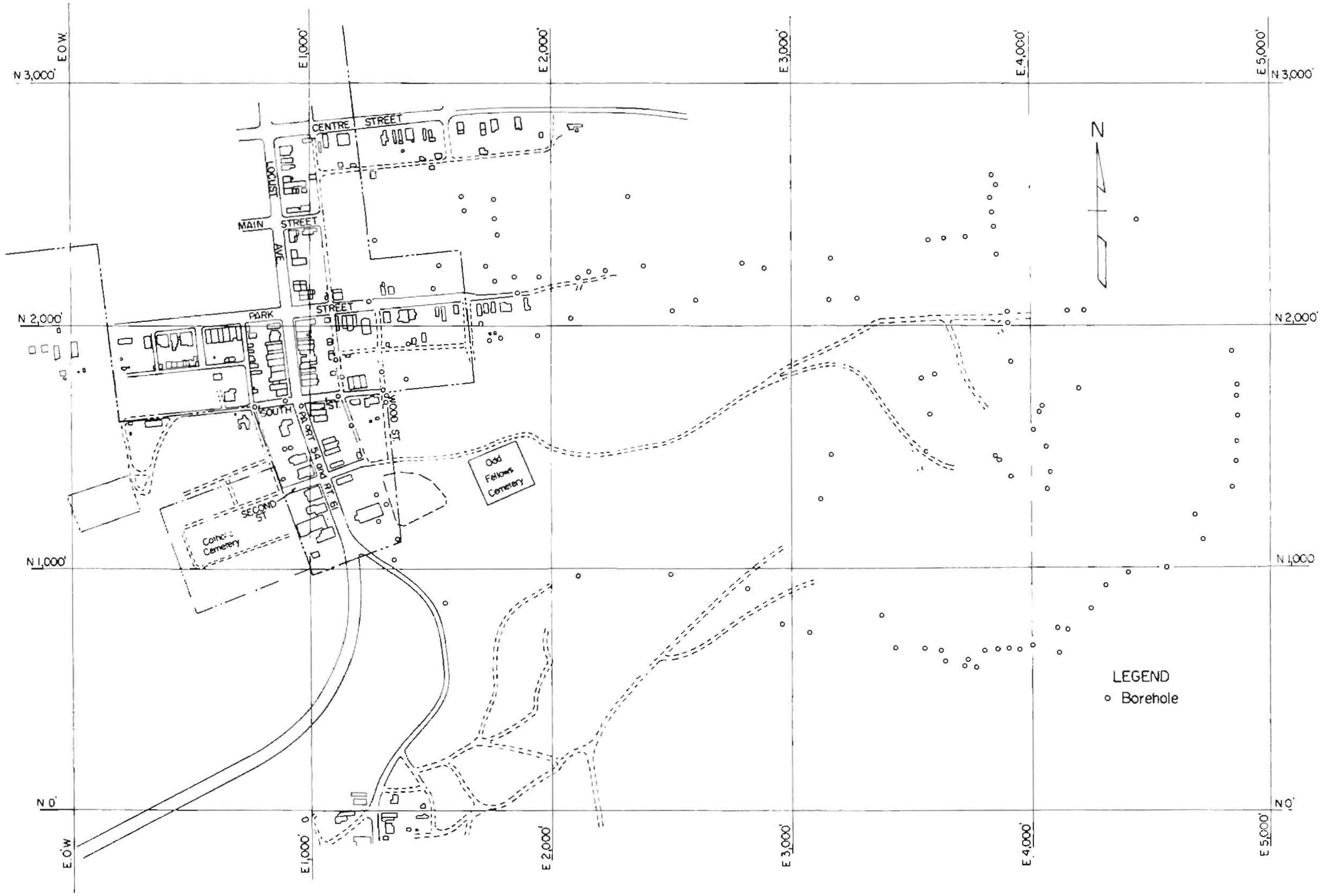

N 3,000'
N 2,000'
N 1,000'
N 0'
E 0 W.
E 1,000'
E 2,000'
E 3,000'
E 4,000'
E 5,000'
N
CENTRE STREET
LOCUST AVE.
MAIN STREET
PARK STREET
SOUTH ST.
WOOD ST.
PA. RT. 54 and RT. 61
SECOND ST.
Catholic Cemetery
Odd Fellows Cemetery
LEGEND
○ Borehole

FIGURE A-3. - Location of boreholes used for underground temperature measurements.

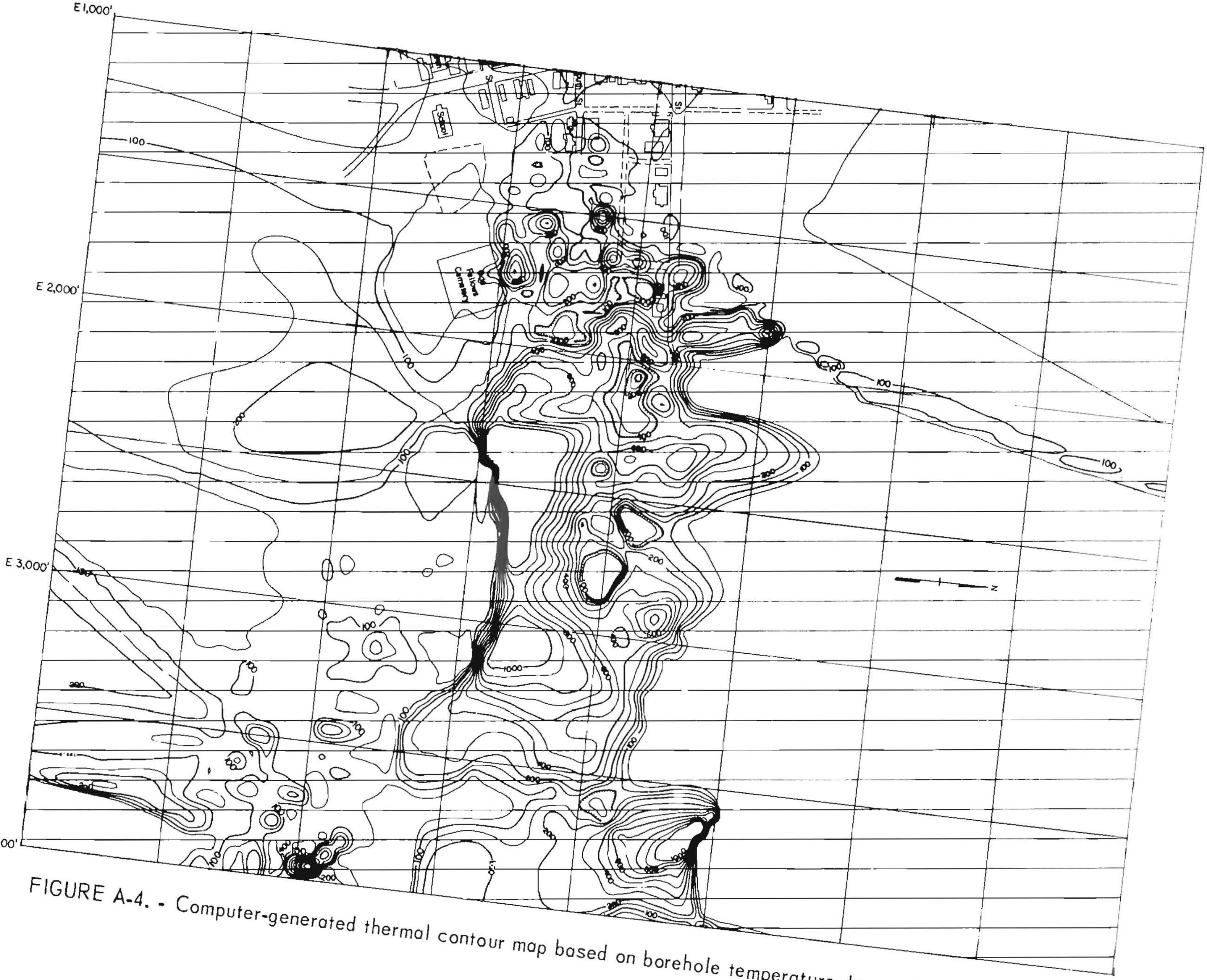

E 1,000'
E 2,000'
E 3,000'
E 4,000'
School
Fillmore Cemetery
St.
N
100
200
400
600
1000

FIGURE A-4. - Computer-generated thermal contour map based on borehole temperature data collected 1967-79.

Where data points are not spaced over a regular grid pattern, the randomly spaced data must be "regularized" using one of several established algorithms. If the nature of the data or its distribution is discontinuous, it is difficult to make valid approximations over a geographic area. Thus, to ensure an effective contouring, it is important to plan a data collection strategy that will provide a suitable distribution and density of data.

Computerized isopach mapping is commonly employed in the coal mining industry to extrapolate borehole core data such as overburden thickness, seam thickness, bottom elevation, areal extent, etc., but has not previously been used to generate underground isotherms. In general, this computer extrapolation produces a contour map that is superimposed on an x-y coordinate map. The computer system used in the current analysis was the "Contour System," a proprietory code of CompuServe Inc., Columbus, OH.

Figure A-4 is a thermal contour map of all the borehole data obtained between 1967 and 1979. The location of the boreholes used in making the contours is not shown. When compared with the temperature zone map (fig. A-2), there is a striking similarity between the areas of high-temperature isotherms and the high-temperature zones despite some anomalies in the contour map. For example, the 200° F contour to the west of the borough is believed to be an artifact of the extrapolation scheme, since the data point nearest to this contour is a single borehole about 300 feet west of the contour. In general, the contour map agrees with the temperature zone map.

To depict the progress of the fire, the computerized data system is also used to construct contour plots for different time periods. Figures A-5, A-6, and A-7 are plots for 1967, 1969, and 1979, respectively. Here the study area is limited to the eastern part of Centralia Borough due to the limited amount of borehole data taken during the time periods considered. In general, the isotherm lines agree with the temperature zone approach. The time sequence shows increasing temperature on the cold side of the 1969-70 flush barrier, possibly due to penetration of the barrier by hot gases.

An advantage of this computerized approach is the speed and ease with which the data can be analyzed and presented once a suitable data file has been constructed. The data can be displayed as 2-D and 3-D (perspective) plots automatically using peripheral plotting equipment. An example of this is the 3-D perspective plot of temperatures for the study area shown in figure A-8. Temperature is shown in the Z-direction, and the heavy grid lines depict areas where the underground temperature is greater than 200° F.

OTHER COMPUTER MAPS

Other information about mine fires can also be depicted by computer mapping. In addition to the subsurface temperature, CO measurements and ventilation estimates were made at each borehole. The CO was usually measured with a colorimetric detector tube; bottle samples were occasionally taken for gas chromatographic analysis. Ventilation draft was estimated by the person taking the measurements according to the following criteria: If smoke was issuing from the borehole, it was considered an updraft; if no smoke was visible at the borehole and suction could be felt if a hand was placed over the borehole, it was listed as a downdraft; lack of both of these indicators was taken to indicate that no pressure differential existed between the surface and the mine workings.

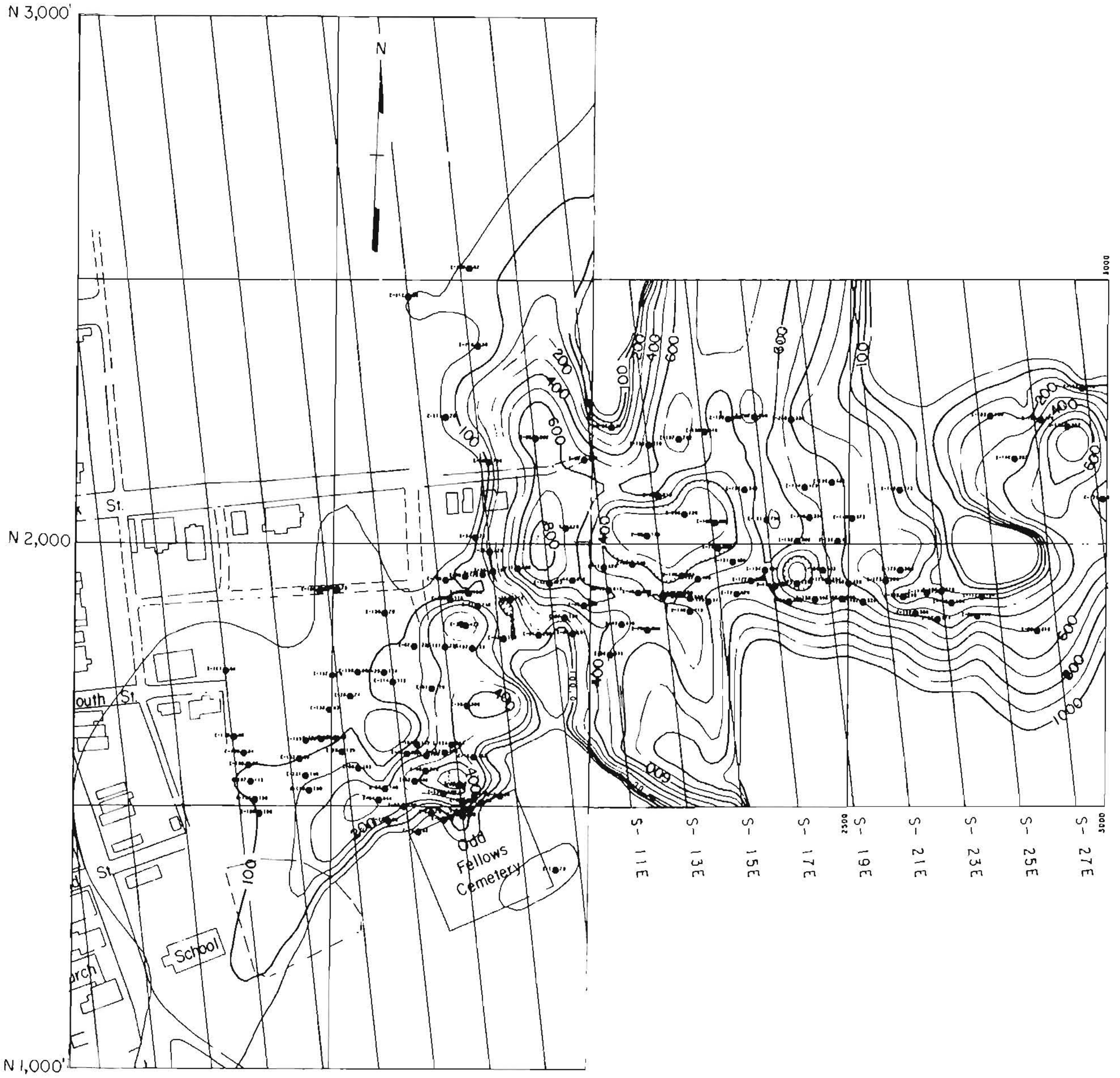

N 3,000'
N 2,000'
N 1,000'
N
St.
South St.
St.
School
Odd Fellows Cemetery
100
200
400
600
800
1000
S- 11E
S- 13E
S- 15E
S- 17E
S- 19E
S- 21E
S- 23E
S- 25E
S- 27E
2500
3000

FIGURE A-5. - Computer-generated thermal contour map based on borehole temperature data for 1967.

In the computer mapping, CO concentration values are plotted according to the location of the boreholes, and contour lines are drawn for values of 0, 0.05, and 0.1 pct (fig. A-9). Areas of higher CO concentration are considered to be in closer proximity to active fire zones.

Ventilation data are plotted as 0, +, or -, and contours are drawn (fig. A-10). Negative or downdraft contours may indicate areas where air is being drawn into the fire. Progressive mapping of positive or updraft contours may be useful in predicting the direction(s) in which the fire will move.

It should be pointed out that computer mapping of temperature and other data has not yet been used to evaluate underground mine fires. In the Centralia case, the computed isothermal contours were used only to verify the manually constructed temperature plots. However, with sufficient experience and the

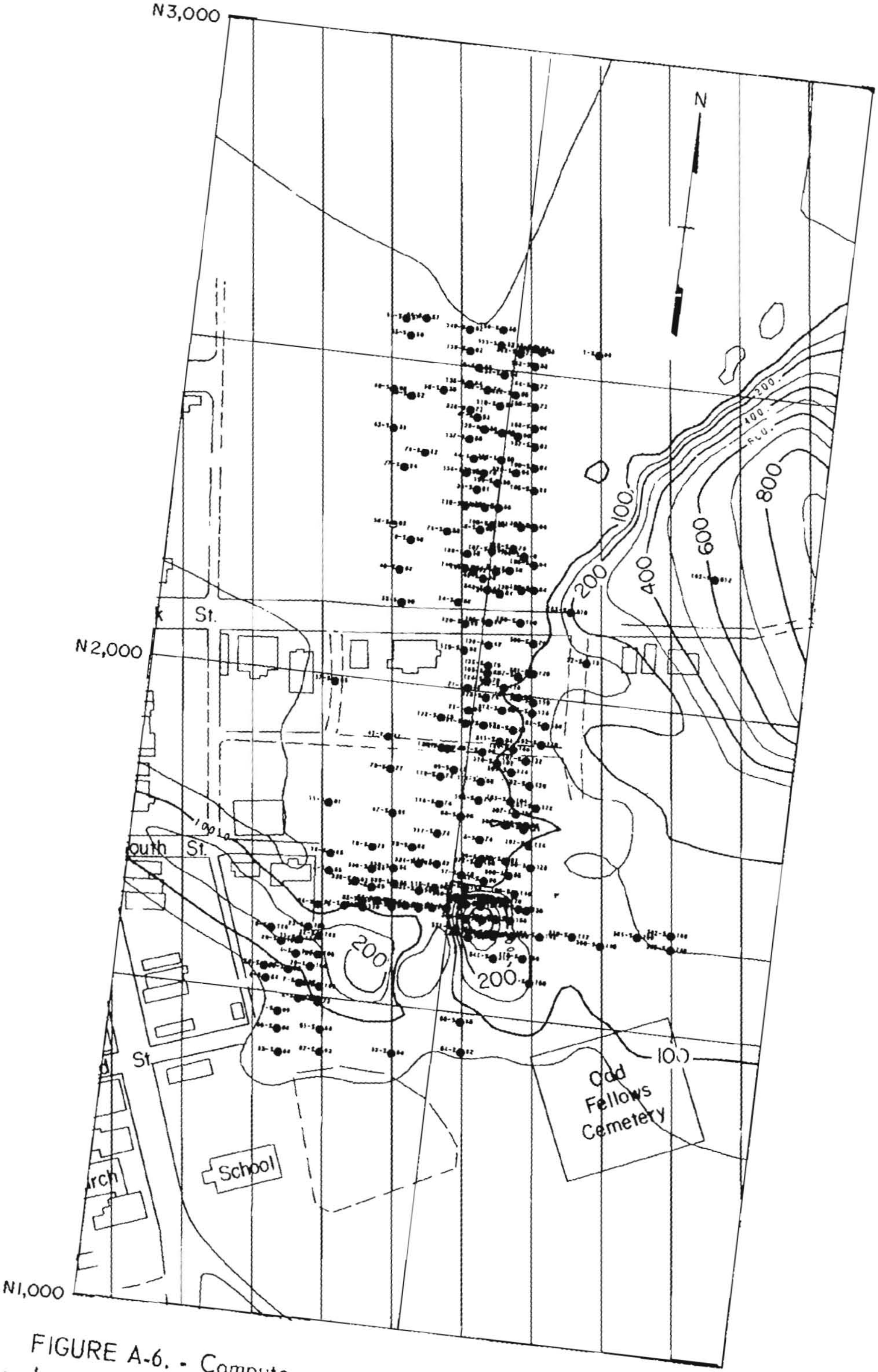

N3,000
N2,000
N1,000
N
k St.
outh St.
d St.
School
rch
Odd Fellows Cemetery
100
200
400
600
800
100
200
200
100

FIGURE A-6. - Computer-generated thermal contour map based on borehole temperature data for 1969.

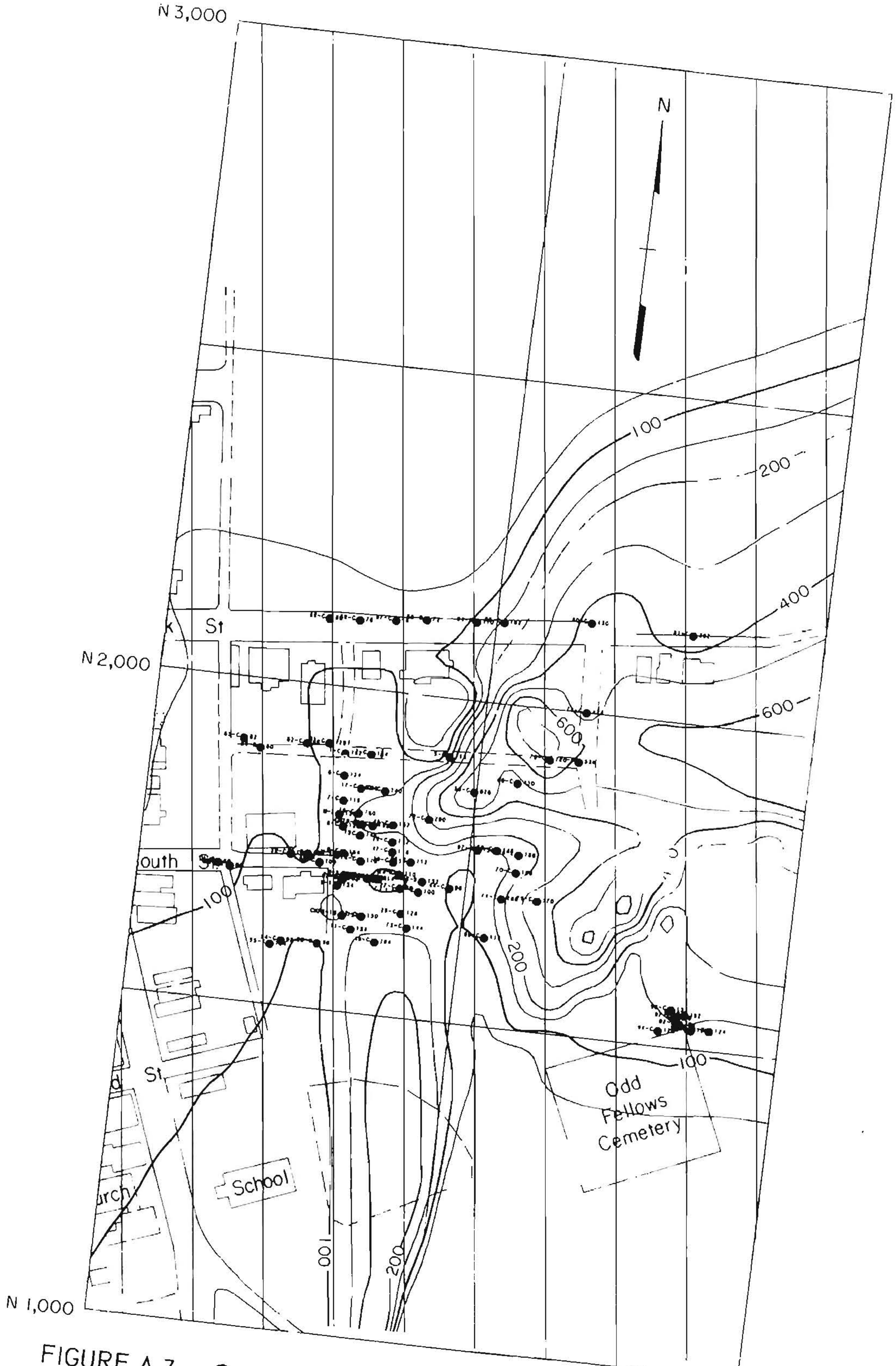

N 3,000
N 2,000
N 1,000
N
100
200
400
600
600
200
100
100
200
St
South St
St
School
Odd Fellows Cemetery

FIGURE A-7. - Computer-generated thermal contour map based on borehole temperature data for 1979.

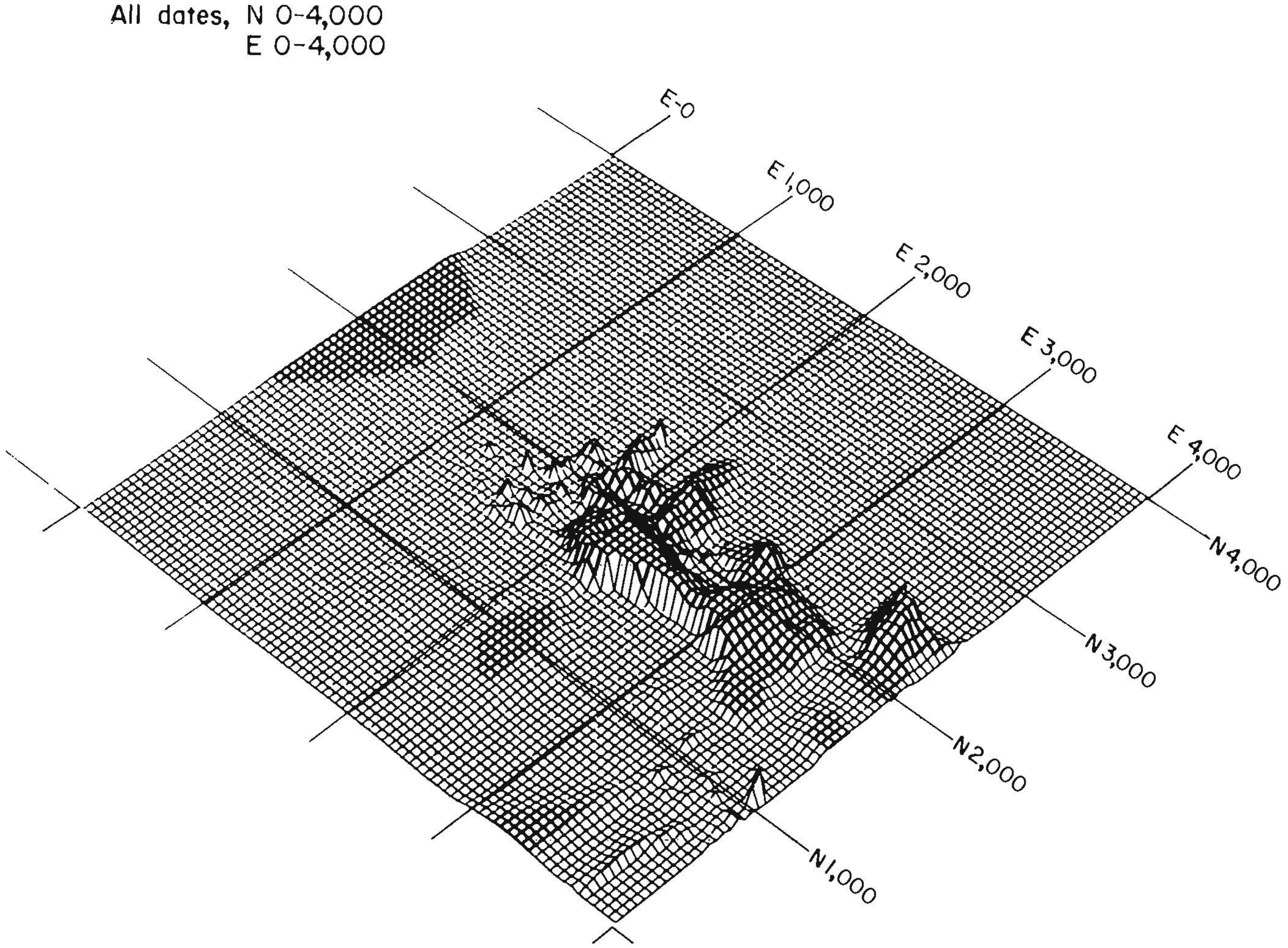


FIGURE A-8. - Three-dimensional perspective of temperatures in study area.

development of a suitable data base, computer mapping could be used to define fire zones, predict direction of fire movement, and monitor the progress of fire control efforts.

THERMAL INFRARED MAPPING

Thermal infrared mapping is a method of remote sensing by which a large area can be surveyed in a short time to identify areas of relative surface temperature. The thermal image reproduced shows contours representing areas of like temperature. Using an airplane to fly over the survey area, the heat radiated from the surface of the earth is detected by an optical mechanical scanner and recorded on magnetic tape. This heat is in the form of electromagnetic energy, which falls within the infrared band of the electromagnetic spectrum; the wavelength generally used in detecting this energy is between 8 and 14 μm (21). An infrared detector sensitive to temperature differences on the order of 0.1° C converts the radiant energy into an electrical signal, which is recorded on tape and later played back onto film in a laboratory to produce the visual image of the temperature differences. On a thermal infrared image, the relative brightness of an area is proportional to the heat being radiated from the surface at that point. When used to define the area of an underground mine fire, it is only possible to infer where the most intense burning is occurring or where the active burning fronts are located. Because the image represents only surface temperatures, when the fire is at a depth of more than 30 m below the surface, it was found that it can be detected by remote sensing only in areas where the heat has been conveyed

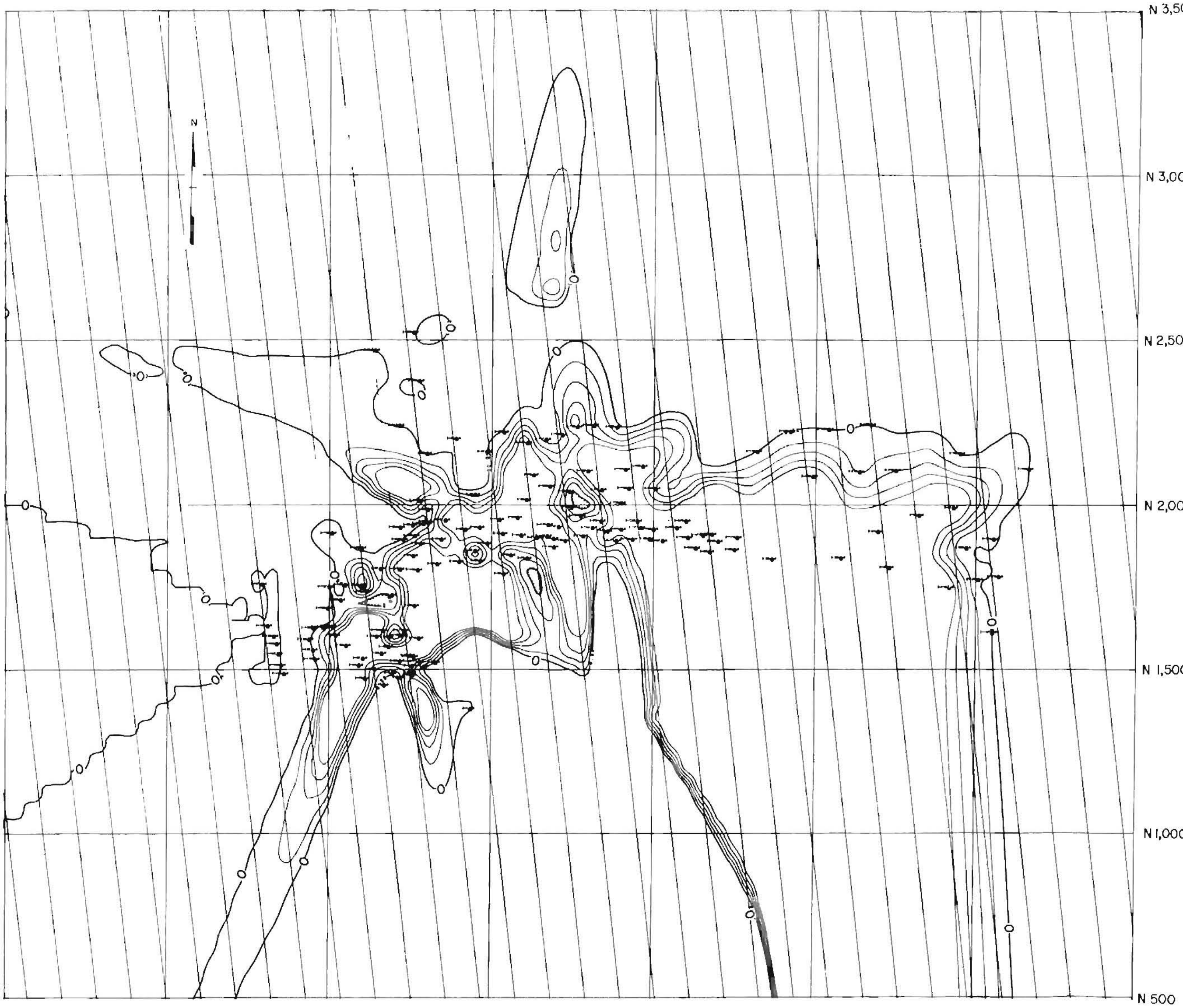


FIGURE A-9. - Computer-generated contour map of CO concentrations based on borehole measurements.

to the surface by convection through cracks in the strata or where the fire has burned long enough for the heat to be conducted to the surface (21).

Infrared mapping of the Centralia area was done in the spring of 1980 (16). This effort involved initial photogrammetric mapping, which served as a reference for the thermal infrared imagery. The survey area covered approximately 205 acres. A planimetric-topographic map was prepared at a scale of 1 inch=100 feet, based on aerial photography. Survey control for the mapping effort was provided by the Bureau.

Thermal infrared imagery of the study area was collected using a thermal scanner with a sensitivity range of 8 to 13 µm. To optimize aerial coverage, two parallel flights were made in the same direction with an area of lateral overlap. These flights were made just before dawn to minimize the effect of solar radiation from the surface and thus provide a better indication of subsurface temperature. The survey was conducted following several days of dry weather to minimize the influence of the moisture content of the soil, which has been found to have an effect on the radiant emittance of a surface.

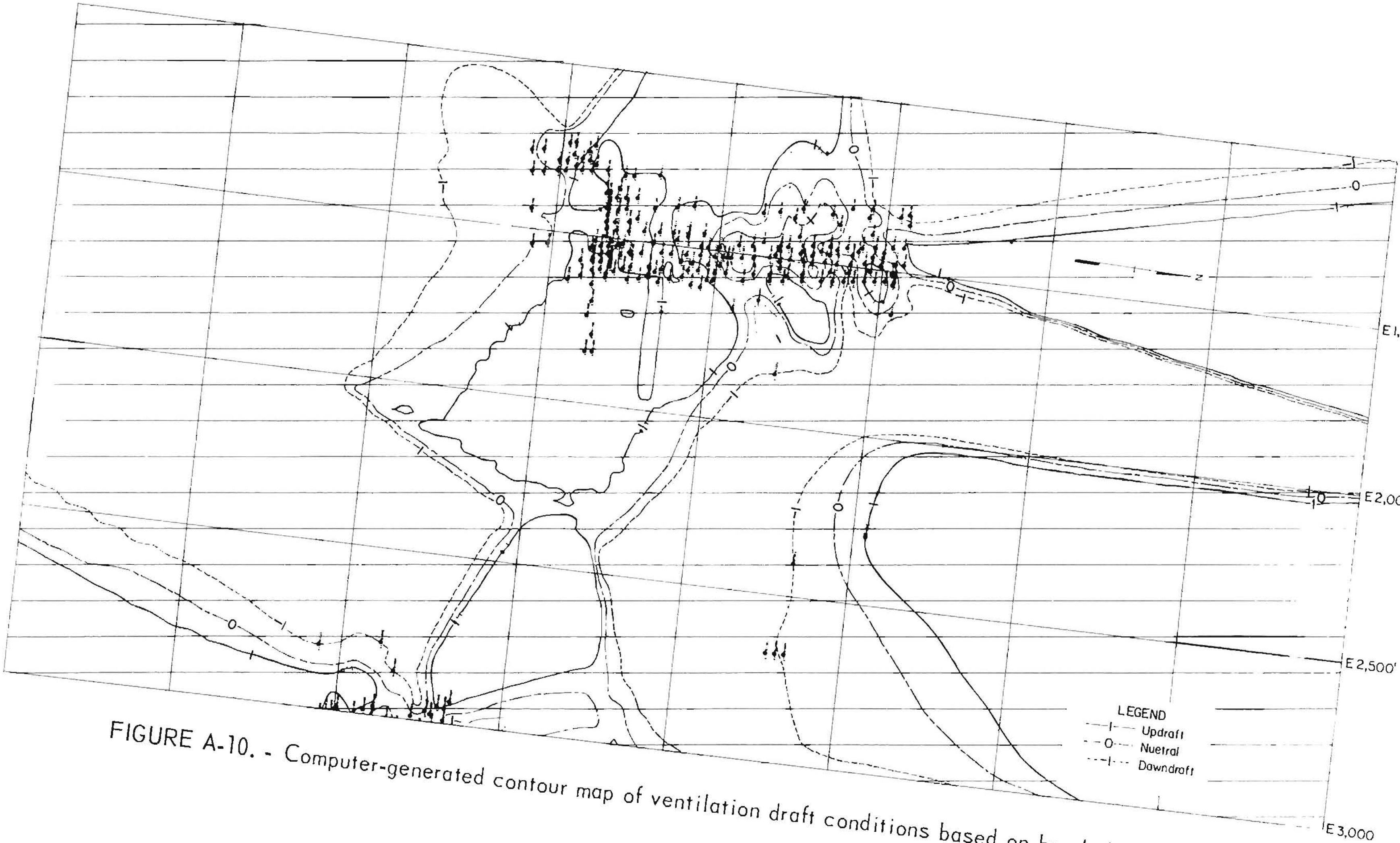

E1,000'
E1,500'
E2,000'
E2,500'
E3,000
LEGEND
Updraft
Nuetral
Dawndraft

FIGURE A-10. - Computer-generated contour map of ventilation draft conditions based on borehole observations.

The scanner data were recorded in analog form and then converted to digital form and processed by computer to produce gray scale maps showing the distribution of temperature intensity. From these, a "false" color map was produced where different colors were assigned to represent different temperature intervals. Since no actual ground temperature measurements were made as a reference for the aerial imagery, the colored thermal contours do not represent specific temperature intervals, but do provide a qualitative picture showing areas of relative temperature and the location of highest temperature.

The final contour maps were developed from the computer-generated color images by matching the digitized thermal data to the aerial reference photographs. At this point, corrections were made to remove tangential distortion in the imagery. The final printout was at a scale that corresponded with the maps of plotted borehole data. The image produced shows a correlation with known surface points where temperatures on the surface are elevated or where vapor is escaping from underground. This form of remote sensing is useful in preliminary planning of a fire control strategy since it provides a way of quickly defining the approximate areas of high temperature.

MODEL CONSTRUCTION

Another useful tool in the assessment of the extent of fire at Centralia was a model of the surface and coalbed structures. Using such a model it was possible to clearly visualize how the fire is moving through the Buck Mountain Seam, across the anticline into the south dip. Also, the problems of flushing and excavation imposed by the steep pitch of the beds become very apparaent from the model.

Figure A-11 is a sketch of the model. A relatively simple and inexpensive procedure was used to construct it. Section map details (every 108 feet) were traced directly onto thick plastic sheets, which were then cut along the surface contour to yield a scale of 1 inch=100 feet. Details of the underground stratigraphy are depicted by colored tapes, which represent the various coal seams, the water table, and even some mine entries and pillars. The heavy plastic sheets were then mounted along a slotted table to form an accurate 3-D representation of the Centralia Borough fire region. By maintaining the same

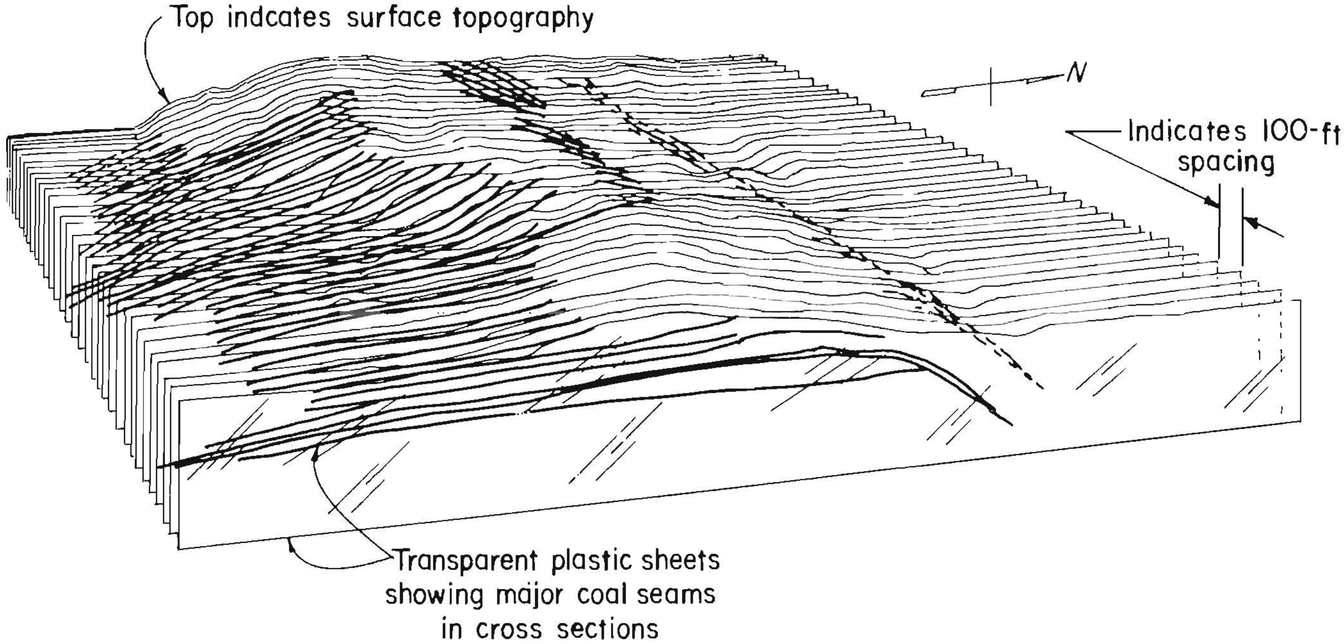
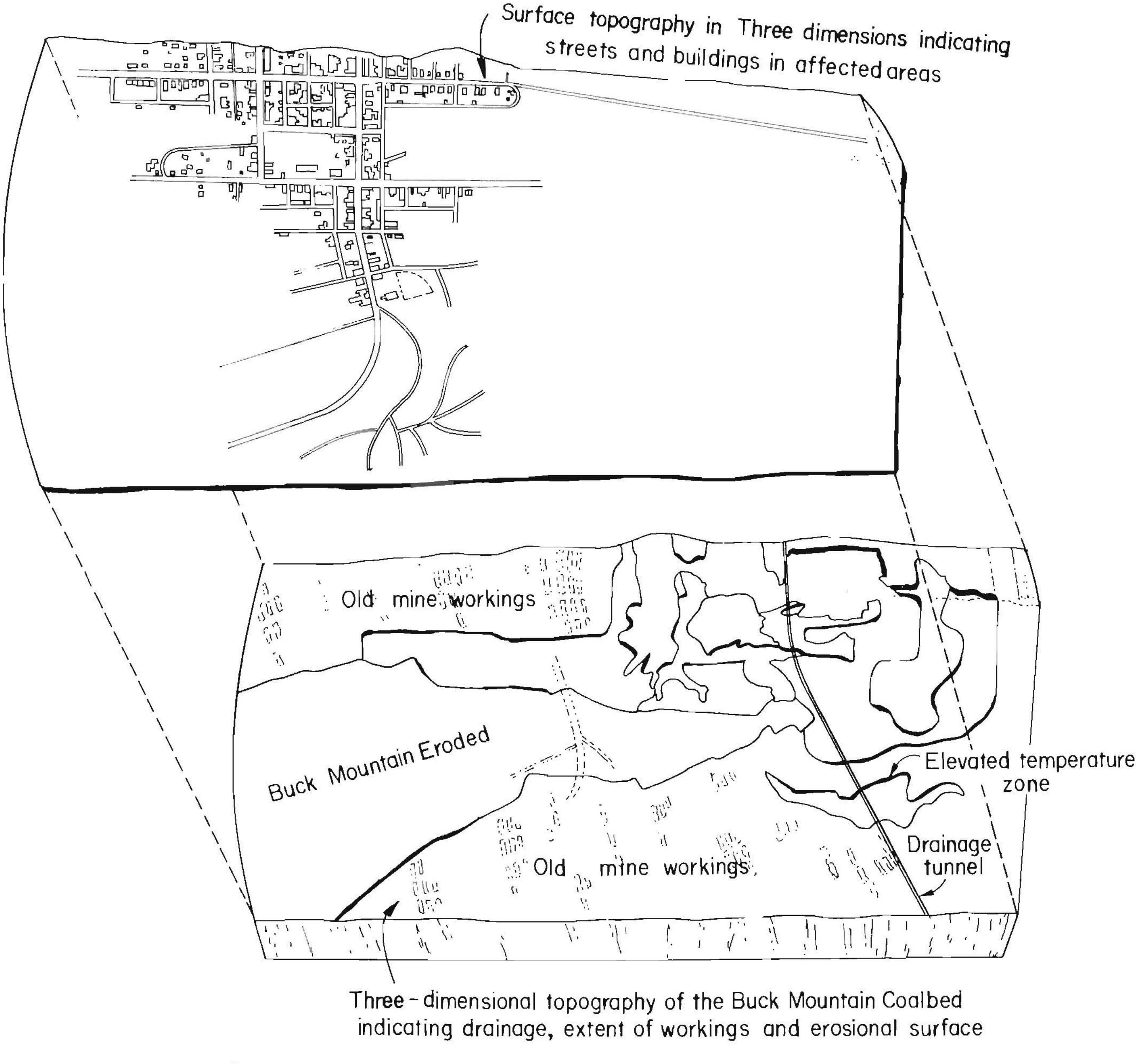

Top indcates surface topography
N
Indicates 100-ft spacing
Transparent plastic sheets showing major coal seams in cross sections

FIGURE A-11. - Sketch of sectional model.

scale as the surface map, a transparent overlay of the surface map readily allows underground details to be referenced to surface structures. In addition to the sectional model, a more elaborate structural model of the Centralia region was constructed that could be taken apart to show the surface and the underlying coalbeds (fig. A-12). The increased comprehension these models provide indicates that construction of similar models for future fire projects, when section maps are available, would be extremely valuable.

SUMMARY

The available techniques used to define the boundaries of an underground fire are useful diagnostic tools within their limitations. They provide an approximation of the location and extent of a fire and, when used in combination, can substantiate the evidence provided by one technique alone. With the further refinement of methods such as these, it should also become possible to predict the direction in which a fire is progressing and the speed of propagation.



Surface topography in Three dimensions indicating streets and buildings in affected areas
Old mine workings
Buck Mountain Eroded
Elevated temperature zone
Drainage tunnel
Old mine workings
Three-dimensional topography of the Buck Mountain Coalbed indicating drainage, extent of workings and erosional surface

FIGURE A-12. - Sketch of three-dimensional structural model.

APPENDIX B.--ANALYSIS OF AIR SAMPLES

The presence of combustion gases in enclosed areas is the most serious hazard associated with the Centralia mine fire. The Bureau of Mines has regularly monitored the levels of carbon monoxide, carbon dioxide, oxygen and methane in homes where unusual concentrations were detected. In addition to the readings taken by the 15 monitors installed in area homes, bottle samples also have been collected periodically for laboratory analysis of gas concentrations. The results of this analysis are shown in the following table.

TABLE B-1. - Laboratory analysis of air samples collected in surface areas of the Centralia fire zone

Location	Sampling date	Composition, vol pct			
		Carbon dioxide	Oxygen	Methane	Carbon monoxide
Residence A:					
Middle bedroom at crack in north wall.	04/23/80	0.16	20.79	0.00	0.0000
Middle bedroom at floor register......		.12	20.83	.00	.0000
Basement rear at rafter right.........		.58	20.37	.00	.0000
First floor, rear room, waist high....	05/02/80	.25	20.73	.00	.0000
Do................................	05/09/80	.13	20.84	.00	.0000
Basement wall, rafter high............		.08	20.90	.00	.0000
Second floor, front room, waist high..		.07	20.91	.00	.0000
First floor, rear room, waist high....	05/15/80	.11	20.84	.00	.0001
Basement at ecolyzer..................		.14	20.82	.00	.0001
Second floor, front room, waist high..	05/15-22/80	.08	20.87	.00	.0000
Background reading....................	05/24/80	.05	20.90	.00	.0000
Basement..............................		.08	20.88	.00	.0000
Second floor, wall....................	07/10-12/80	.17	20.78	.00	.0000
Basement, west wall, at rafters.......		.09	20.88	.00	.0000
First floor, floor level..............	08/03/80	.06	20.88	.00	.0000
Second floor, middle room, wall.......	09/23/80	.06	20.92	.00	.0000
Residence B:					
First floor baseboard at stairway to second floor.........................	04/23/80	.48	20.49	.00	.0000
Basement at bottom of steps, waist high................................		.99	19.97	.00	.0000
Basement, oil burner pit..............		7.69	13.77	.00	.0000
Basement, west wall, waist high.......	05/02/80	.91	20.11	.00	.0000
Do................................	05/09/80	.33	20.63	.00	.0000
Basement, oil burner pit..............		.03	17.65	.00	.0000
Basement, east wall, waist high.......		.27	20.69	.00	.0000
Basement, oil burner pit..............	05/15-22/80	6.80	13.74	.00	.0000
Basement, west wall, waist high.......		.49	20.49	.00	.0000
Basement, east wall, waist high.......		.21	20.73	.00	.0000
Basement, oil burner pit..............	05/27-31/80	.06	20.90	.00	.0002
Residence C, service station:					
Basement, base of washer platform.....	04/23/80	10.04	11.04	.02	.0000
Basement, crack in floor at oil burner		4.49	16.40	.01	.0000
Basement, oil tank, waist high........	05/02/80	.88	20.15	.00	.0000
Basement, floor at washer platform....	05/09/80	10.24	11.57	.05	.0000
Basement, floor at oil burner.........		3.35	17.33	.00	.0000
Basement, floor by oil burner.........	05/15/80	1.92	18.97	.00	.0000
Basement, at washer platform..........		7.90	13.75	.02	.0000
Garage, southwest corner, waist high..	05/27-31/80	1.26	19.59	.00	.0000
Basement, waist high..................		.55	20.38	.00	.0000
Basement, at ecolyzer during flushing.		.15	20.81	.00	.0002
Do................................		.50	20.42	.00	.0002
Basement..............................	07/09/80	.39	20.59	.00	.0000

TABLE B-1. - Laboratory analysis of air samples collected in surface areas of the Centralia fire zone--Continued

Location	Sampling date	Composition, vol pct			
		Carbon dioxide	Oxygen	Methane	Carbon monoxide
St Ignatius School:					
Basement, south wall, 6 inches above floor	05/02/80	0.08	20.90	0.00	0.0000
Basement, social room near stage, floor level	05/09/80	.12	20.84	.00	.0000
Basement, south wall by stage, floor level	05/15-22/80	.09	20.86	.00	.0000
Basement, near stage, floor level	06/04/80	.07	20.88	.00	.0001
Basement, at ecolyzer		.14	20.81	.00	.0001
Basement, south wall, base of stage	08/07/80	.14	20.84	.00	.0000
Residence D:					
Basement	07/09/80	.24	20.73	.00	.0002
Basement, waist high	07/10-12/80	.28	20.67	.00	.0000
Basement, coal bin		2.73	18.12	.00	.0000
Do	08/07/80	9.37	11.42	.02	.0002
Residence E:					
Basement, northwest corner, floor level	05/02/80	.07	20.91	.00	.0000
Basement	05/15-22/80	.05	20.90	.00	.0000
Do	07/09/80	.15	20.80	.00	.0000
Residence F:					
Basement, northwest corner	05/15-22/80	.06	20.90	.00	.0000
Basement	08/03/80	.07	20.89	.00	.0000
Living room		.11	20.84	.00	.0000
Residence G:					
Basement, south wall	05/27-31/80	.05	20.91	.00	.0000
Parlor	09/06/80	.04	20.92	.00	.0003
Odd Fellows Cemetery:					
Mine cave hole northeast of cemetery	07/10-12/80	2.34	18.33	.00	.0007
Do		5.05	15.38	.00	.0013
Residence H: Basement, northwest corner, waist high	05/02/80	.05	20.92	.00	.0000
Residence I: Water meter pit	07/09/80	8.36	12.76	.00	.0000

APPENDIX C.--EXCAVATION PLANS, COST, AND PROJECT WORK

The four excavation plans proposed for controlling the Centralia mine fire involve digging out an area of the fire to the outcrop of both the north dip and the south dip of the Buck Mountain Coalbed. This effectively prevents the spread of the fire north toward Centralia and south toward Byrnsville. Checking the progress of the fire can be accomplished either by total excavation or by a combination of excavation and trenching, which limits the fire to a confined area where it will burn itself out.

In general, excavation is a means of controlling an underground fire by physically removing the burning material and overburden above it, applying water to cool the material and quench the fire, and backfilling and grading the area once the fire has been extinguished. Excavation of a fire barrier or trench involves digging out an open trench from the surface to the bottom of the coalbed wide enough that heat from the fire side will not be transferred across the trench to ignite the coalbed on the cold side.

The proposed excavation options provide alternatives in the amount of excavation required versus the remaining fire area isolated by barriers. In plan A, the entire fire area would be excavated. This involves digging out 83 acres to a depth of 300 feet on the north dip of the Buck Mountain Coalbed and 57 acres to a depth of 200 feet on the south dip.

In plan B, the fire area beneath the borough would be completely excavated and trenches would be used to isolate the area underlying unpopulated areas. The excavated area lies on the western edge of the fire area on the north dip, and would be 1,400 feet long and 300 feet deep. From this excavated area, a northern isolation trench would extend eastward, paralleling a southern isolation trench along the south dip of the coalbed. Both trenches would be 2,400 to 2,600 feet long and 300 feet deep. The northern and southern trenches would be connected along the eastern edge by a third isolation trench, 1,800 feet long and 300 feet deep. All these trenches would be 50 feet wide at the coalbed. Under this plan, 60 acres would be excavated on the north dip and 29 acres on the south dip, leaving a 51-acre fire area to burn itself out.

In plan C, a cutoff trench and an isolation trench would be used to isolate the fire within the existing natural boundaries. The cutoff trench on the north dip would extend from the outcrop north 1,100 feet to the water table and be 540 feet deep, involving 12 acres. The isolation trench on the south dip would be 2,600 feet long, 200 feet deep, and involve 24 acres. An isolated fire zone of 151 acres would remain.

Plan D combines complete excavation of the area of the fire beneath the borough with the use of a cutoff and an isolation trench. On the north dip, the excavated area would be 1,400 feet long and 300 feet deep, with a cutoff trench 540 feet deep extending from this area 400 feet to water level; total area excavated on the north dip would be 40 acres. On the south dip, an isolation trench 2,600 feet long and 200 feet deep would be used to confine the fire in that direction, involving an additional 24 acres. An isolated fire area of 77 acres would remain.

Tables C-1 and C-2 show the overall tasks and costs for each excavation plan into the work required on the north dip and that on the south dip.

TABLE C-1. - Breakdown of project work by type of excavation plan

	Excavation, MM cu yd	Backfill, MM cu yd	Quenching, MM cu yd	Coal recovery, M tons	Number of holes
Excavation plan A:					
North dip............	21.0	14.7	8.4	797.0	41
South dip............	14.0	9.8	5.6	361.0	44
Total...........	35.0	24.5	14.0	1,158.0	85
Excavation plan B:					
North dip............	11.9	8.3	3.3	417.0	41
South dip............	3.9	2.7	1.1	35.0	44
Total...........	15.8	11.0	4.4	452.0	85
Excavation plan C:					
North dip............	2.9	2.0	0	22.1	41
South dip............	3.5	2.5	1.0	34.6	44
Total...........	6.4	4.5	1.0	56.7	85
Excavation plan D:					
North dip............	8.5	6.0	3.4	311.1	41
South dip............	3.5	2.5	1.4	34.7	44
Total...........	12.0	8.5	4.8	345.8	85

TABLE C-2. - Breakdown of costs by type of excavation plan, millions

	Excavation, at $2.25/cu yd	Backfill, at $1.00/cu yd	Quenching	Property value, at $30,000/ structure	Total	Coal recovery, at $20/ton	Total[1]
Excavation plan A:							
North dip.......	$47.1	$14.7	$0.3	$3.3	$65.4	$15.9	$49.5
South dip.......	31.6	9.8	0	0	41.4	7.2	34.2
Total......	78.7	24.5	.3	3.3	106.8	23.1	83.7
Excavation plan B:							
North dip.......	26.7	8.3	.3	3.3	38.6	8.3	30.3
South dip.......	8.8	2.7	0	0	11.5	.7	10.8
Total......	35.5	11.0	.3	3.3	50.1	9.0	41.1
Excavation plan C:							
North dip.......	6.4	2.0	.3	4.0	12.7	.4	12.3
South dip.......	8.0	2.5	0	0	10.5	.7	9.8
Total......	14.4	4.5	.3	4.0	23.2	1.1	22.1
Excavation plan D:							
North dip.......	19.1	6.0	.3	3.4	28.8	6.2	22.6
South dip.......	8.0	2.5	0	0	10.5	.7	9.8
Total......	27.1	8.5	.3	3.4	39.3	6.9	32.4

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[1] Total does not include an estimated $500,000 for assessment and monitoring of boreholes.

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